# COORDINATED SCIENCE LABORATORY

# PROGRESS REPORT FOR THE JOINT SERVICES ELECTRONICS PROGRAM

FOR THE PERIOD
APRIL 1, 1988, THROUGH MARCH 31, 1989
FOR
CONTRACT N00014-84-C-0149



UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

JSEP ANNUAL PROGRESS REPORT

For the Period

1 April 1988 through 31 March 1989

**Joint Services Electronics Program**
**Contract N00014-84-C-0149**

Monitored by the
Office of Naval Research

William Kenneth Jenkins
JSEP Principal Investigator
Coordinated Science Laboratory

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SECURITY CLASSIFICATION OF THIS PAGE

# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

| | |
|---|---|
| 1a REPORT SECURITY CLASSIFICATION<br>Unclassified | 1b RESTRICTIVE MARKINGS<br>None |
| 2a SECURITY CLASSIFICATION AUTHORITY | 3 DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release; distribution unlimited |
| 2b DECLASSIFICATION/DOWNGRADING SCHEDULE | |
| 4 PERFORMING ORGANIZATION REPORT NUMBER(S) | 5 MONITORING ORGANIZATION REPORT NUMBER(S) |
| 6a NAME OF PERFORMING ORGANIZATION<br>Coordinated Science Lab<br>University of Illinois<br>6b OFFICE SYMBOL (If applicable)<br>N/A | 7a NAME OF MONITORING ORGANIZATION<br>Office of Naval Research |
| 6c ADDRESS (City, State, and ZIP Code)<br>1101 W. Springfield Ave.<br>Urbana, IL 61801 | 7b ADDRESS (City, State, and ZIP Code)<br>Arlington, VA 22217 |
| 8a NAME OF FUNDING/SPONSORING ORGANIZATION<br>Joint Services Electronics Program<br>8b OFFICE SYMBOL (If applicable) | 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>N00014-84-C-0149 |
| 8c ADDRESS (City, State, and ZIP Code)<br>Arlington, VA 22217 | 10 SOURCE OF FUNDING NUMBERS<br>PROGRAM ELEMENT NO. \| PROJECT NO. \| TASK NO \| WORK UNIT ACCESSION NO. |

11. TITLE (Include Security Classification)
Third Annual Progress Report

12. PERSONAL AUTHOR(S)
W. K. Jenkins, Principal Investigator

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| Annual Progress | FROM 4/1/88 TO 3/31/89 | 6/30/89 | 94 |

16. SUPPLEMENTARY NOTATION

| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |
|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | |
| | | | |
| | | | |

19. ABSTRACT (Continue on reverse if necessary and identify by block number)


This is the third annual progress report of the research conducted at the Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, under the sponsorship of the Joint Services Electronics Program from 1 April 1988 through 31 March 1989. The research areas include Solid-State Electronics, Quantum Electronics, Electromagnetics, Information Systems, and Electronics Research (discretionary Director's unit). This report summarizes the areas of research, identifies the most significant results, and lists the publications sponsored by JSEP as well as other sponsoring agencies.


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|---|---|---|
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>Unclassified | |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL | 22b. TELEPHONE (Include Area Code) | 22c. OFFICE SYMBOL |

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

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## RESEARCH AREA: Electronics Research

# EXECUTIVE SUMMARY

## I. Summary of the Program

The current Joint Services Electronics Program contract at the Coordinated Sciences Laboratory, University of Illinois at Urbana-Champaign, began on October 1, 1986, and will continue through September 30, 1989. This report reviews accomplishments during the period April 1, 1988, through March 31, 1989, and describes changes in the program that have occurred during the third year. The present program includes 22 work units that cover five major technical areas: (1) Solid State Electronics, (2) Quantum Electronics, (3) Electromagnetics, (4) Information Systems, and (5) Electronics Research (discretionary Director's unit). Solid-State Electronics includes six units primarily devoted to the growth, characterization, and device fabrication of compound semiconductor materials. Quantum Electronics includes three units: one unit studies charge density waves (CDWs) in superconducting materials, and two units deal with plasmas and excited state chemistry of gases. Electromagnetics contains two units: one concentrates on monolithic millimeter-wave ICs with microstrip antennas and the second on the design and analysis of nonreflecting surface structures to control radar scattering characteristics. Information Systems includes ten units covering important topics in computers, control, communications, and signal processing. Detailed discussions of individual accomplishments are presented in the main body of this report. In addition, two items that have been selected from among the many significant contributions are highlighted in the following paragraphs. The first "JSEP Significant Accomplishment" is the conception and demonstration of a new mechanism of tunnel injection in MODFET structures. This work was done under the new Unit 24 that was established at the start of the second year of the program. The second item is the completion of the University of Illinois EpiCenter, which was partially supported with JSEP discretionary funds.

During the last year the JSEP Director, Professor W. K. Jenkins, has continued to rely on the recently established JSEP Internal Advisory Committee to help establish direction and policy for the JSEP-sponsored research. Professors K. Hess, M. B. Pursley, and T. N. Trick are presently serving as members of the committee in the areas of Physical Electronics, Electronic Systems, and VLSI Circuits and Computer Systems, respectively. The committee played a vital role in the planning and restructuring of the Illinois JSEP Program that was proposed in June 1989 for the next three years.

## II. JSEP Significant Accomplishments (April 1, 1988 - March 31, 1989)

### Conception and Demonstration of a New Mechanism of Tunnel Injection (Unit 24)

Professors Adesida, Kolodzey, and Leburton recently reported the conception and experimental verification of a new mechanism of tunnel injection into the active region of MODFET structures. Injection occurs through a tunnel junction parallel to the MODFET channel and is the basic mechanism for sophisticated high-speed multi-terminal devices. Two novel transistor structures were proposed—the BITFET and the TIFET—that exploit the new injection principle in a configuration leading to Negative Differential Resistance (NDR) characteristics. Theoretical estimates of the relevant time constants indicate possible operation in the 100 GHz range.

With barrier height equal to the band gap, the use of tunnel junctions has the advantage of reducing thermionic emission competing with the tunneling current and results in high peak-to-valley NDR ratios that are suitable for high-power microwave devices.

TIFET structures have been fabricated and tested in our laboratory. Experimental I-V characteristics show evidence of tunneling in the 2-D channel of the MODFET across the tunnel junction (see Figure 1). A patent application for the new devices has been filed by University Patents, Inc.

**Completion of the University of Illinois EpiCenter (Unit 23)**

In late 1988, construction of the University of Illinois EpiCenter was completed and a dedication ceremony was held in November of 1988 to commemorate its opening. The EpiCenter is a world-class facility that consists of seven MBE chambers interconnected by high-vacuum transfer tubes. Having the chambers, each of which is dedicated to a different type of material growth and characterization, interconnected by vacuum lines allows samples to be moved from one growth environment to another without external contamination. Since the planning for this new facility was begun about five years ago and the construction has taken two years, the completion of this project is a major accomplishment. All of the JSEP discretionary funds provided under Unit 23 of the current contract were applied toward the purchase of several MBE chambers that will support future MBE research in the JSEP program. Since the EpiCenter is described in detail under Unit 23, further details will not be presented in this section.

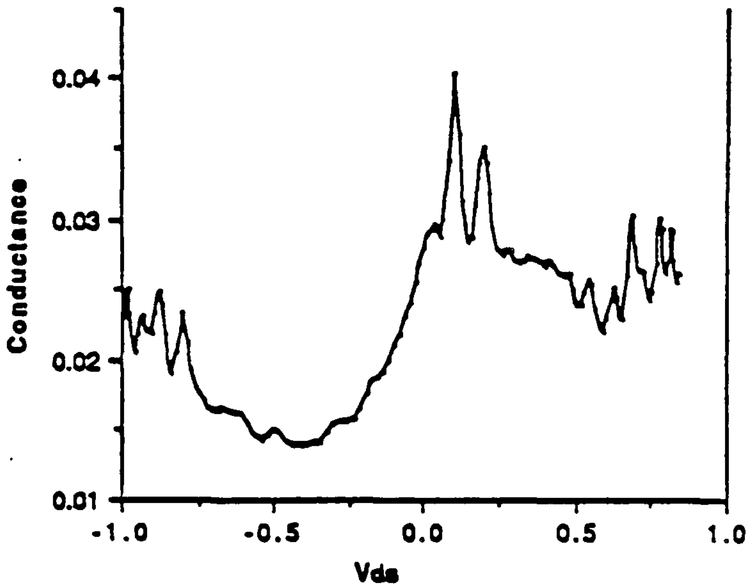


Fig. 1. Conductance vs. $V_{ds}$ for GaAs/AlGaAs TIFET Device, $I_{sb}$ = +5mA, $V_{gs}$ = 1V

## WORK UNIT NUMBER 1

TITLE: Crystal Growth from the Vapor Phase and Controlled Doping of Equilibrium and Metastable Semiconductor Alloys: Ion-Surface Interactions

### SENIOR INVESTIGATORS:

J. E. Greene, Research Professor
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### SCIENTIFIC PERSONNEL AND TITLES:

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L. Markert, Research Assistant
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J.-P. Noël, Research Assistant
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M. A. Ray, Research Assistant

### SCIENTIFIC OBJECTIVE:

The primary objective of this research program is to investigate energetic particle-surface interactions that control the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconductors during vapor-phase crystal growth by UHV ion beam sputtering and accelerated-beam molecular beam epitaxy. In both of these growth techniques, low energy ion-surface interactions allow an efficient coupling of kinetic energy to the growth surface upon condensation, thereby altering the surface reactivity as well as adsorption and adatom diffusion kinetics allowing single crystal film growth at lower temperatures, much more precise control over dopant incorporation probabilities and depth distributions, and the growth of unique metastable alloys. This work is being pursued from both an analytical and an experimental point of view in order to establish a detailed understanding of fundamental film growth mechanisms.

### SUMMARY OF RESEARCH:

**Incorporation Probabilities and Depth Distributions of Thermal and Accelerated Dopants in Semiconductors Grown by MBE**

Most common n- and p-type dopants used in bulk Si technology and many dopants used in bulk GaAs provide problems in MBE film growth due to either low dopant incorporation probabilities and/or high surface-segregation rates. The problem is especially acute in MBE Si. We have attacked these problems on two fronts. (1) As discussed in the last two annual reports, we have developed a general time-dependent model, which combines thermodynamic and kinetic elements, for describing the incorporation of thermal dopants into films during deposition. (2) We have investigated the use of low-energy primary and secondary accelerated-ion doping during MBE growth to demonstrate increases in $\sigma$ by more than five orders of magnitude, abrupt doping profiles with no indication of segregation-induced broadening, and excellent electrical properties. Primary-ion doping experiments

were carried out using a new ion source that was designed and constructed as part of this research project.

Our dopant incorporation model accounts for dopant surface segregation and allows elemental incorporation probabilities $\sigma$ and depth-dependent concentration profiles $C(x,t)$ to be calculated as a function of experimental parameters such as film and dopant material, deposition rate, incident dopant flux, film growth temperature, etc. Calculated profiles from arbitrarily complex doping schedules for both thermal and accelerated dopants are in good agreement with experimental results for dopants in MBE Si, GaAs, and $Ga_{1-x}Al_{1-x}$ As. In addition, we have used the model to predict critical temperatures for transitions in dopant segregation regimes, dopant-induced surface structural phase transitions, and changes in dopant/surface reaction paths leading to large changes in surface binding energies and hence incorporation probabilities. All of these effects have now been observed experimentally. We have recently predicted that there should exist a narrow growth-temperature range over which abrupt doping profiles can be obtained for Al, a p-type dopant which exhibits severe surface segregation, in MBE Si Our preliminary experimental results are in agreement showing, for the first time, abrupt modulation-doped Al profiles.

We have extended our dopant incorporation measurements, reported for In last year, to include Sb, an important n-type dopant in Si technology. The incorporation probability $\sigma$ of thermally coevaporated Sb ranges from $10^{-3}$ to $10^{-5}$ at typical Si MBE growth temperatures. Sb also exhibits severe surface segregation with steady-state coverages up to a full monolayer. This not only gives rise to broad profiles but also limits the maximum usable doping concentrations to $\leq 5x10^{17}-10^{18}$ $cm^{-3}$ due to the necessity of using extremely large dopant fluxes that result in the production of high concentrations of structural defects with a corresponding decrease in carrier mobilities.

Using the ion sources described previously, we have carried out a detailed investigation of the incorporation of accelerated $Sb^+$ ions in MBE Si(100) with acceleration voltages $V_{Sb^+}$ of 50, 100, 200, 300, and 400 V at growth temperatures $T_s$ ranging from 550 to 1050 °C. $\sigma_{Sb^+}$ was found to be up to five orders of magnitude higher than obtainable with thermal Sb beams. In fact, $\sigma_{Sb^+}$ was unity for $V_{Sb^+} \geq 300$ V at $T_s \leq 850$ °C. At higher growth temperatures, bulk diffusion becomes appreciable giving rise to Gibbsian surface segregation and hence dopant loss by desorption. At lower acceleration potentials, $\sigma_{Sb}$ was temperature and deposition-rate dependent. However, even at $V_{Sb^+} = 50$ V and $T_s \geq 650$ °C, $\sigma_{Sb^+}$ was still more than an order of magnitude higher than for thermal doping. Moreover, surface-segregation induced profile broadening $\Delta_{Sb}$, which for thermal-beam doping was $\geq$ 100 nm/concentration-decade for $T_s \leq 650$ °C, was less than the depth resolution of the SIMS measurement, i.e. $\Delta_{Sb^+} \leq 15$ nm/concentration-decade. In fact, we have used accelerated-beam doping to grow the first two-dimensional $\delta$-doped MBE Si layers and demonstrated resonant tunneling.

"Potential-enhanced" or recoil-implantation doping has been proposed by several researchers in Europe as another possible technique for overcoming the problems associated with doping in MBE Si. In this approach, a fraction of the Si beam is ionized and accelerated to recoil implant surface-segregated dopant species This, however, does not solve the profile broadening problem since a steady-state doping concentration cannot be achieved until a steady-state surface coverage is reached. We have carried out detailed measurements of $Si^+$ ion current densities as a function of accelerating potential for several Si evaporator designs and determined the recoil implantation cross-sections as a function of $E_{Si^+}$ for In and Sb The results show that optimum operating conditions require $E_{Si^+}$ to be $\geq 1000$ eV leading to residual lattice damage. (Lattice damage has recently been reported by an IBM group using 1000 V Sb recoil-implant doping). Moreover, this technique is of no value for dopants such as As or P which also exhibit surface segregation but whose surface lifetimes are so short that appreciable coverages are only obtained at a very low deposition temperatures where growth-related and ion-induced defects cannot be annealed out.

We have extended our earlier continuum dopant incorporation model to formulate a discrete atomistic lattice model which accounts for the detailed reconstructed surface structure. The present

version is a five site (including surface, bulk, and three intermediate sites) transition-state model. The site potentials are determined from modulated-beam mass spectrometry (MBMS) and thermally-stimulated desorption (TSD) measurements using both thermal and accelerated beams. Surface segregation potentials were determined from calibrated SIMS analyses of as-deposited modulation-doped layers grown as a function of $V_{Sb^+}$, $T_s$, and the deposition rate R. The model calculations were found to describe the entire set of $\sigma_{Sb^+}(V_{Sb^+}, T_s, R)$ data extremely well and provide new insights into dopant incorporation mechanisms and low-energy ion/surface interactions. It is clear, for example, that the incorporation mechanism for accelerated In and Sb doping changes dramatically below 200 eV.

We have designed, operated, and characterized a new adjustable-grid, multiaperature, ion source. The capability for *in-situ* relative lateral motion of the grid allows beam steering and alignment during operation. The grid separation distance is also adjustable *in-situ* allowing independent control over the beam current and voltage while maintaining minimum beam divergence. Decreases in beam divergence angle by as much as a factor of three over a comparable fixed grid source were obtained. The dependence of the measured beam divergence on the source operating conditions and grid geometry were explained based upon an ion optics model.

**Electronic and Optical Properties of Accelerated-Ion Doped MBE Si**

A combination of *in situ* low-energy and reflected high energy electron diffraction (RHEED and LEED), plan-view and cross-sectional transmission electron microscopy (TEM and XTEM), SIMS, temperature-dependent Hall measurements, low-temperature photoluminescence (PL), and deep-level transient spectroscopy (DLTS) were used to investigate the structure, dopant distribution, and electrical properties of MBE Si(100) films grown at 800 °C with either 200 eV $In^+$ or 150 eV $Sb^+$ accelerated-dopant beams. The incorporation probabilities were found to be unity. A comparison between total dopant concentrations determined by calibrated SIMS measurements and dopant concentrations obtained from Hall data shows that both In and Sb were incorporated into substitutional, electrically-active, sites. The concentration ranges examined so far are $5\times10^{15}$-$2\times10^{18}$ $cm^{-3}$ for In, well above the equilibrium solid-solubility limit, and $10^{16}$-$3\times10^{19}$ $cm^{-3}$ for Sb, more than an order of magnitude above the highest values obtainable by thermal doping without introducing high structural defect concentrations. In all cases, the films were found by TEM and XTEM analysis to be dislocation free with no indication of residual ion-induced damage.

Carrier mobilities were found to be equal to, or higher than, the best reported values for bulk Si. In fact, hole mobilities measured in $In^+$-doped films were the highest ever reported for In-doped Si and were much higher than mobilities for annealed In-implanted Si. Temperature-dependent (77-400 K) mobilities of $In^+$-doped films were well described by theoretical calculations, with no adjustable parameters, including lattice, ionized impurity, neutral impurity, and hole-hole scattering. The full effective mass tensor describing the non-isotropic and non-parabolic band structure was used. Doping profiles in modulated structures were abrupt and *in situ* AES and RHEED analysis showed no indication of significant dopant surface accumulations as were observed during the growth of thermally-doped films. Thus, under the present growth conditions, radiation-induced defects were annealed out at a faster rate than they were produced resulting in no residual damage.

Recently, we have obtained the first high quality photoluminescence ever reported from MBE Si films. In these experiments, we used a combination of low-temperature (4.2 K) PL and DLTS to characterize Si(100) films doped with $E_{As^+}$ = 200, 500, and 1000 eV $^{75}As^+$ ions during growth by molecular-beam epitaxy on $n^+$ Sb-doped substrates at temperatures $T_s$ of 650 and 800 °C. Sharp no-phonon, transverse-optical, and transverse-acoustic phonon assisted bound-exciton (BE) peaks associated with As dopant species, together with broader, weaker, Sb-related BE peaks, were the dominant PL features obtained from 5-$\mu$m-thick layers. No peaks ascribable to residual ion-induced damage were observed in films grown at 650 °C with $E_{As}$ = 200 eV or $T_s$ = 800 °C with $E_{As}$ = 200, 500, and 1000 eV. No electron traps were observed by DLTS.

**Effects of Low-Energy Ion/Surface Interactions on the Nucleation and Growth Kinetics of Films Deposited from the Vapor Phase**

The increasingly stringent requirements of sophisticated thin-film device and processing technologies provide a strong impetus for obtaining better control over the microchemistry and microstructure of as-deposited layers as well as for devising lower temperature growth techniques. Low energy ion irradiation of the substrate and film during deposition is presently being used by laboratories across the world in a variety of beam and plasma-based film growth techniques in order to provide an efficient coupling of kinetic energy to the growth surface to alter reactivity as well as adsorption, adatom diffusion, nucleation, and growth kinetics.

Our group has been modeling low-energy ion/surface interaction effects that are common to a variety of growth techniques and has carried out some of the first definitive experiments under well-controlled ultra-high vacuum environments to probe fundamental mechanisms. The initial results of this work were described in the last annual report.

Over the past year, we have developed MBMS and TSD techniques for measuring binding energies, and hence inferring binding sites, of low-energy accelerated condensing species. As a reference point, we have determined not only the two-dimensional phase diagram for In on Si(100)2x1 but also the binding energy of In in each of the surface phases. This is the first time both complete structural and energetic information has been available for any metal overlayer system on Si.

The structure and surface morphology of In overlayers on Si(100) surfaces were investigated as a function of substrate temperature and surface coverage using low-energy and reflection high-energy electron diffraction as well as Auger electron spectroscopy. Desorption kinetics of adsorbed In was studied with modulated-beam desorption and temperature-programmed desorption spectroscopies. Indium was found to grow on Si(100) according to a Stranski-Krastanov mechanism with the initial formation of several two-dimensional phases preceding the nucleation and growth of three-dimensional In islands. Binding energies and frequency factors were extracted from the desorption measurements using a model based on first-order desorption from several interdependent surface phases. First-order and zeroth-order kinetics were observed for the total desorbing flux from coexisting surface phases.

The use of low-energy $In^+$ condensing species was found to completely change the nucleation and growth mechanism. Nucleation densities were increased by several orders of magnitude, the surface diffusivity was enhanced, and complete three-dimensional overlayer was obtained at much lower coverages. Initial measurements of binding energies as a function of ion energy have been completed.

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## WORK UNIT NUMBER 2

TITLE: Studies of Transport Phenomena in Semiconductors

**SENIOR INVESTIGATOR:**

K. Hess, Research Professor

**SCIENTIFIC PERSONNEL AND TITLES:**

I. C. Kizilyalli, Research Assistant
J. Higman, Research Assistant
S. Manion, Research Assistant

**SCIENTIFIC OBJECTIVE:**

This research involves the study of basic properties of semiconductors, semiconductor-heterolayers, new device concepts, and device simulation. Both theoretical and experimental methods are employed in each of these categories. We are examining a variety of hot electron phenomena and their effects on present and future device performance. The experimental studies concern mainly electronic transport in heterolayers in high electric and high magnetic fields, while the theoretical studies are based on Monte Carlo methods and, generally speaking, the use of large computational resources.

**SUMMARY OF RESEARCH:**

In the past year, we have completed our research on the hot electron heterojunction diode ($H^2ED$), the velocity modulation transistor (VMT), and basic investigations of hot electron effects in bulk AlGaAs, the high electron mobility transistor, and in real space transfer devices. This work has led to several publications and the demonstration of microwave frequency operation of the $H^2ED$.

A major effort has been made to explain and simulate transport at very high energies in silicon based devices. We have investigated the possibility of cold cathods. Cold cathods are p-n junction devices in which electrons are heated up so much that they can overcome the work function and be emitted out of the semiconductor material. The electron emission in such devices can be modulated extremely fast and, therefore, presents opportunities that standard hot cathods cannot offer. Since the emission of electrons occurs at electron energies of 2eV or higher in the conduction band, these devices offer a testing ground of high-field Monte Carlo theories and have revealed very interesting physics, which has been described in an extensive publication [6].

In cooperation with R. W. Dutton (Stanford), we have applied our Monte Carlo codes to high-field transport in MOSFET's and have made a first attempt to investigate the possibility of merging standard device simulations and Monte Carlo methods. We have explained the detailed physics of hot electron effects such as substrate current and impact ionization. We have found that for devices with channel length longer than one micrometer, a single Monte Carlo run on the basis of the field profiles as derived by standard simulations (PISCES) explains all experimental results well. We are currently developing methods for smaller feature sizes. The results have been described in reference [7].

## INTERACTION AND/OR TECHNOLOGY TRANSFER:

The work on merging Monte Carlo investigations with standard device simulations has been performed in cooperation with the group of R. W. Dutton at Stanford. The work on hot electrons in AlGaAs was in cooperation with K. Brennan (Georgia Tech) and M. A. Littlejohn (North Carolina State).

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# WORK UNIT NUMBER 4

TITLE: Basic Studies of the Optical and Electronic Properties of Defects and Impurities in Compound Semiconductor Epitaxial Layers and Related Superlattices

## SENIOR INVESTIGATOR:

G. E. Stillman, Research Professor

## SCIENTIFIC PERSONNEL AND TITLES:

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S. S. Bose, Research Assistant
M. A. Haase, Research Assistant
M. H. Kim, Research Assistant
N. Pan, Research Assistant
A. Reed, Research Assistant
B. Lee, Research Assistant
I. Szafranek, Research Assistant
D. Sengupta, Research Assistant

## SCIENTIFIC OBJECTIVE:

The objective of this research unit is to contribute to our understanding of impurity incorporation mechanisms, sources, and defects and to improve our understanding of the influence of growth conditions on impurities and defects in semiconductor materials that will be important for new multiple-layer compound heterostructure devices. It includes developing new characterization techniques that will extend the range of impurity concentrations over which quantitative analysis is possible. These techniques will lead to better control of high-purity growth and accurate doping levels in epitaxial layers grown by metalorganic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), and chemical beam epitaxy (CBE) or gas source molecular beam epitaxy (GSMBE) growth techniques that are most important for the preparation of multiple layer heterostructures for high-speed electronic and optoelectronic devices.

## SUMMARY OF RESEARCH:

The capability of donor identification in n-type and certain p-type high-purity GaAs samples using low-temperature magnetophotoluminescence with a superconducting solenoid and a one-meter, double slit grating spectrometer was established. By correlating photothermal ionization measurements with the magneto-photoluminescence measurements on the same samples, the $1s-2p_0$ and $1s-2p_{-1}$ two-electron transitions of the neutral donor-bound excitons ($D^\circ$,X), corresponding to the common donor species in GaAs, have been identified.

This technique has been extended to the identification of the residual donor species, Si, S and Ge, in high-purity undoped p-type epitaxial GaAs, grown by metalorganic chemical vapor deposition and arsenic trichloride vapor phase techniques, using the magnetic splittings of "two-electron" replicas of donor-bound exciton transitions at low temperature (~1.8K) and at a high magnetic field (9.0 T). This technique permits identification of donors in certain high-purity p-type GaAs samples that have sufficient neutral donor-bound exciton recombination but in which donor species cannot be identified

by photothermal ionization spectroscopy or any other technique.

Carbon is a ubiquitous impurity in essentially all epitaxial growth techniques for gallium arsenide. Although carbon is from Group 4 and is potentially amphoteric, it has never been observed as a donor in GaAs However, it is a common residual acceptor as well as a useful intentional p-type dopant, especially for thin epitaxial layers and multiple quantum well structures because of its low diffusion coefficient.

We have studied the source of residual (unintentional) carbon impurities in MBE GaAs by intentional injection of CO into an MBE system. High-purity Si-doped MBE GaAs layers grown with and without the intentional introduction of CO gas have been characterized by Hall effect measurements, photoluminescence, and photothermal ionization spectroscopy. The results indicate that CO itself is not the source of residual C acceptor impurities in MBE GaAs samples. The observations of the correlation of residual C impurity incorporation with the residual CO gas in the MBE growth chamber suggest that the partial pressure of CO, $P_{CO}$, gives a quantitative indication of background levels of unidentified hydrocarbons that are the source of C acceptors.

Our results, combined with the earlier results discussed above, show that the C source in MBE reactors that is responsible for the residual C acceptors in MBE GaAs samples is not CO but probably other hydrocarbons. The elimination of these residual hydrocarbons in the MBE reactor was claimed to be an important step for the growth of high-purity GaAs. Further experiments would be desirable to confirm this hypothesis. Since the hydrocarbons, including $CH_4$, are desorbed relatively faster than CO, their background levels can eventually reach or go below the detection limit of the mass spectrometer. Even though the partial pressures of hydrocarbons are near or below the detection limit, the C impurity concentration can still be high if the sticking coefficients of the hydrocarbons are near unity. The residual partial pressure of CO is a qualitative indication of the cleanliness of the growth reactor and of the background levels of hydrocarbons that are the sources of C acceptors.

In MOCVD growth, C is an intrinsic impurity because of the metal organic sources, so it is important to be able to minimize the incorporation of these intrinsic C impurities except when they are desired for doping of the epitaxial layers.

Metalorganic chemical vapor deposition (MOCVD) of epitaxial layers of III-V compounds is among the most widely used growth technique. As greater understanding and control of the MOCVD growth process have been achieved, improvements in surface morphology, layer thickness uniformity, interface quality, and purity have led to ongoing improvements in device quality and performance.

One important area that is not fully understood is the process of residual C acceptor incorporation in GaAs grown by the MOCVD technique using TMGa and $AsH_3$. There is some question about which chemical species carries the C impurity to the epitaxial layer. The methyl groups of the TMGa molecules are widely believed to be the source of carbon. On the other hand, hydrocarbon impurities were detected in the residue from fractionally distilled TMGa. Growths using redistilled TMGa [21] were found to have lower C acceptor concentrations [21]; thus, these hydrocarbon residues may be a source of carbon. The residual C acceptor concentration in GaAs has been found to be dependent on several growth parameters: V/III ratio [22-27], substrate temperature [23-27], substrate orientation [26,27], and the reactor pressure [28]. These are all important pieces of information needed to understand the sources and incorporation mechanisms of residual C; however, a full understanding of C incorporation has proved difficult based on these facts alone.

The mechanisms governing C incorporation can be understood in terms of the chemical reactions. The curve in Figure 1 is a line of constant concentration of surface adsorbed, $AsH_3$*. This line represents the minimum $AsH_3$* concentration needed to prevent deleterious effects. Concentrations of $AsH_3$* below this minimum lead to increased carbon incorporation and/or instabilities in the carrier concentration. The source of carbon can be understood in terms of the concentration of adsorbed $(CH_3)_3Ga$ on the substrate surface and the reactions shown in Figure 2. At low growth temperatures, reaction (2) proceeds at a relatively low rate allowing a large number of $(CH_3)_3Ga$ molecules to reach the substrate. But if the V/III ratio is increased, the abundant $AsH_3$* will react

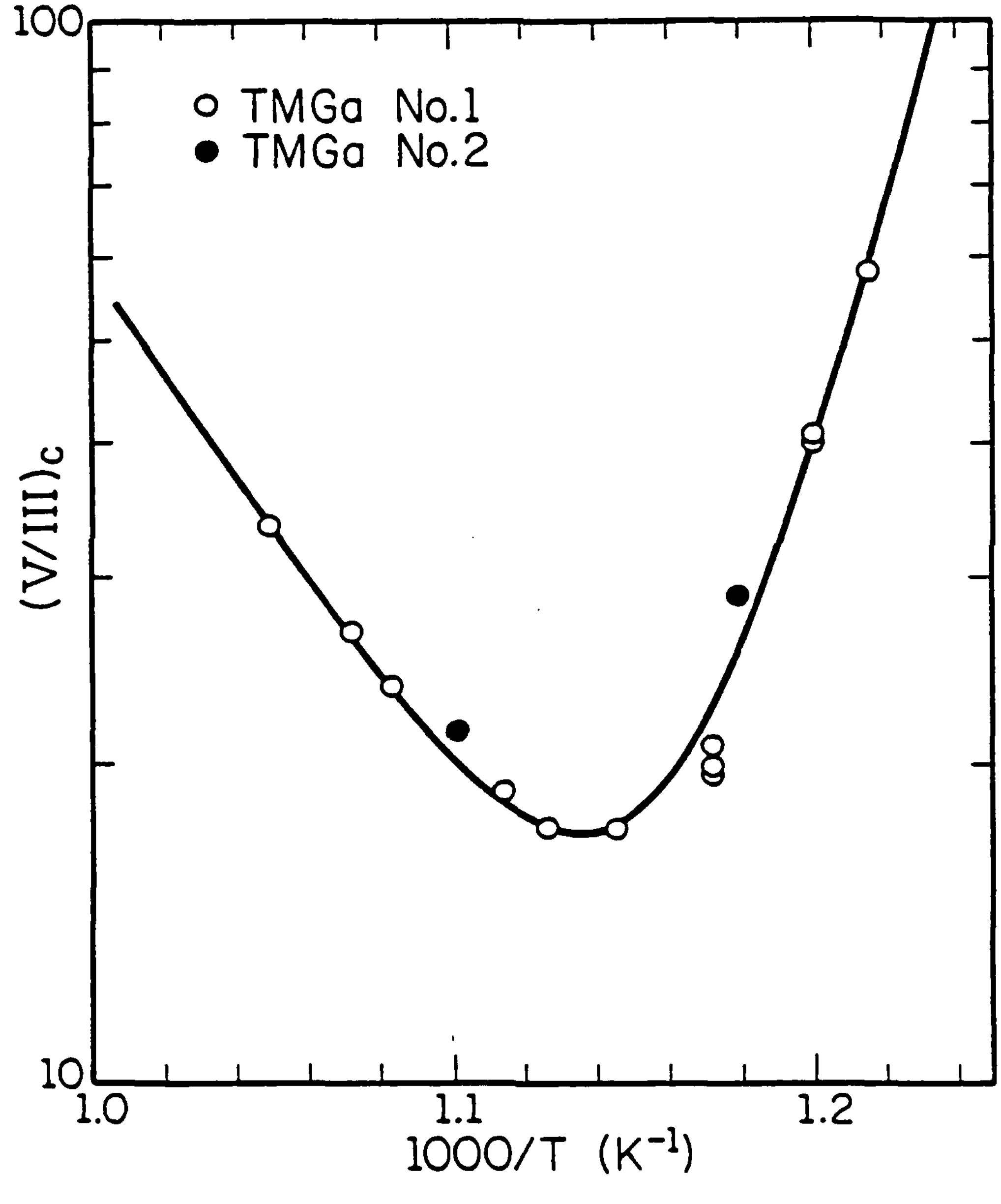


Fig. 1. Temperature dependence of critical V/III ratio.

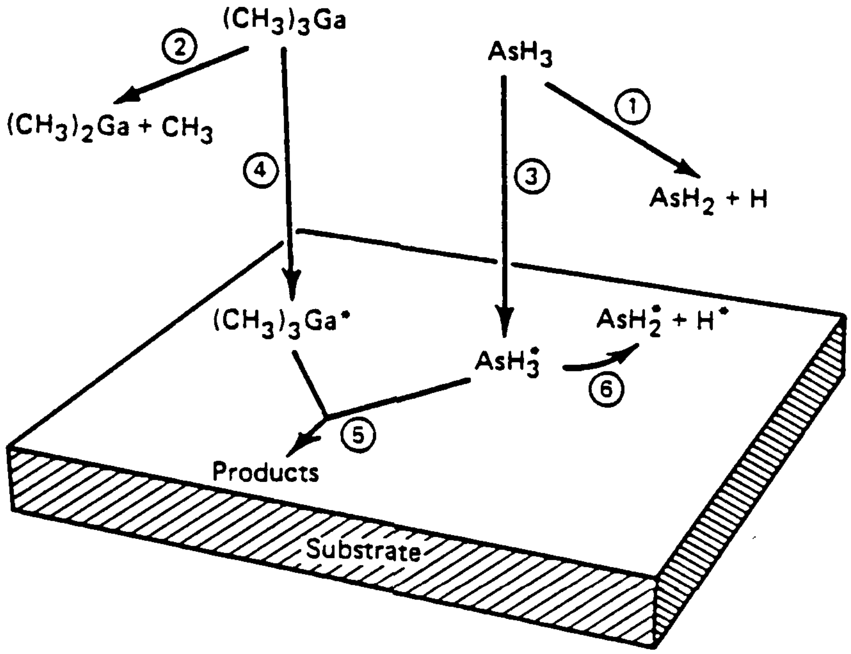


Fig. 2. Drawing of chemical reactions influencing carbon acceptor incorporation.

with the $(CH_3)_3Ga$, the driving reaction (5) at a high rate and reducing $[(CH_3)_3Ga^*]$. This results in reduced carbon incorporation. When the growth temperature is increased, more $(CH_3)_3Ga$ is depleted from the gas via reaction (2) and fewer $(CH_3)_3Ga$ reach the substrate; hence, a smaller V/III ratio is sufficient to provide the requisite quantity of $AsH_3^*$ to drive reaction (5) at a high rate. These reactions account for the low-temperature "arm" of Figure 1. Further increases in the growth temperature will eventually increase the rate of reaction (1) and reduce the concentration of adsorbed $AsH_3$. Increasing the V/III ratio will provide the requisite concentration of adsorbed $AsH_3$ to react with $[(CH_3)_3Ga^*]$ and reduce C incorporation. These reactions account for the high-temperature "arm" of Figure 1. Thus, C incorporation requires that an uncracked TMGa molecule adsorb on the substrate and remain there unreacted. Reactions that interfere with this process result in reduced C acceptor incorporation.

These results are direct evidence that the residual carbon acceptor concentration is controlled by two chemical reaction mechanisms: (1) the removal of the first methyl group from gas phase TMGa, and (2) the removal of the first hydrogen atom from surface adsorbed $AsH_3$. An analysis of the chemical reaction shows that surface adsorbed TMGa is the source of residual carbon acceptors in GaAs grown by MOCVD with TMGa and $AsH_3$ sources. These chemical reactions have been controlled to reduce the C acceptor concentration, resulting in high-mobility GaAs epitaxial layers.

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## WORK UNIT NUMBER 5

TITLE: Heterostructure Electronic Devices by Metalorganic Chemical Vapor Deposition (MOCVD)

**SENIOR INVESTIGATOR:**

J. J. Coleman, Research Professor

**SCIENTIFIC PERSONNEL AND TITLES:**

M. E. Favaro, Research Assistant
T. K. Higman, Research Assistant

**SCIENTIFIC OBJECTIVE:**

The objective of this program is to extend to electronic devices the enormous impact that metalorganic chemical vapor deposition (MOCVD), as a sophisticated epitaxial growth method, has had on optical device research. This involves fundamental studies of the MOCVD process itself for electronic materials, studies of the electronic properties of heterostructure electronic materials, and studies of devices made from these materials. Two specific areas of interest for this research are: (1) continuation of electronic materials analysis including deep-level transient spectroscopy (DLTS) and Shubnikov-de Haas measurements of quantum well heterostructure and superlattice structures, and (2) development of MOCVD-grown real-space transferred electron devices, the heterostructure hot electron diode (HHED), and other electronic devices.

**SUMMARY OF RESEARCH:**

In the preceding two years, we have worked on the heterostructure hot electron diode (HHED). This two-terminal device exhibits pronounced S-shaped negative differential resistance (NDR) due to the transition from tunneling to thermionic emission of electrons incident on a wide gap semiconductor from a lightly doped narrow gap semiconductor. From a Monte Carlo simulation, it has been shown that most of the heated electrons incident on the barrier scatter into the X and L valleys of the drift region. The lower conduction band offsets of the X and L valleys further enhance the thermionic emission of electrons. HHED switching has been experimentally observed at low temperature in devices grown by MOCVD with both single and multiple period barriers. With the incorporation of a single AlAs barrier, room temperature S-shaped NDR has been observed.

In more recent work, the single AlAs barrier has been replaced with a 17-period 40Å GaAs / 50Å AlAs superlattice barrier. The current versus voltage trace of this device at low temperature exhibited a single N-shaped NDR region followed at higher bias by the characteristic HHED S-shaped NDR region. Resonant tunneling through a superlattice generally produces multiple NDR regions due to an expanding high field domain breaking the $E_1$ miniband coupling and a transition to $E_1 - E_2$ tunneling followed by a relaxation to $E_1$ in the high field domain. The relatively wide 40Å barrier and large Γ-point conduction band offset of our structure results in a narrow $E_1$ miniband, which is equivalent to isolated $E_1$ states. We observed no $E_1 - E_1$ tunneling current. Thus, resonant tunneling occurs only when the applied bias aligns the $E_1$ level in one well with the $E_2$ level in the next well. The single NDR region corresponds to the $E_1 - E_2$ tunneling path being present over the entire superlattice. Several single quantum well tunneling experiments have shown that the Γ-point

potential governs the resonance levels in AlAs/GaAs/AlAs quantum well resonant tunneling structures with speculation that the X-point may play a role. Our results support the contention of Γ-point confinement.

Subsequently, this superlattice structure was placed in a magnetic field parallel to the current flow. The magnetic field quantizes the energy of the electrons parallel to superlattice layers into Landau levels. Hence, the total energy of the electrons is given by $E_{n,m} = E_n + (m + \frac{1}{2})h\omega_c$ where n is the subband and $\omega_c = eB/m$ is the cyclotron resonance frequency. When the device is biased at peak resonance, the Landau levels also line up for each value of m. For purely elastic tunneling in the bulk of the superlattice, the tunneling would proceed from an arbitrary Landau level $E_{1,m}$ to $E_{2,m}$ of the next well. Within this model, a device biased at resonance undergoing purely elastic tunneling processes should show no magnetic field dependence for the tunneling current. As the magnetic field is increased, the energy separation between Landau levels began to preclude acoustic phonon emission by the tunneling electrons, effectively limiting the tunneling to the elastic components and thereby reducing the tunneling current. At still larger magnetic fields, the current recovers and then increases with two peaks in the data. These peaks can be interpreted in the following way: as the magnetic field, and therefore, the Landau level energy separation, is increased, the energy separation between an integer number of levels can equal the energy of an optical phonon involved in the inelastic Γ−Γ scattering. The resulting optical phonon would have an energy of 42 meV that corresponds quite well to the experimentally observed "AlAs like" transverse optical phonon modes in GaAs/AlAs superlattices. The entire change in the peak current is only 5%, which indicates the inelastic contribution is small. Thus, the dominant sequential resonant tunneling process in AlAs/GaAs superlattices is elastic tunneling by Γ valley electrons in subbands defined by the large Γ-point conduction band offset.

In addition, we have continued work on the negative resistance field-effect transistor (NERFET) that incorporates the real-space transfer of electrons to effect switching of a source-drain current to a third substrate terminal. In this device, at a critical source-drain electric field, thermionic emission and thermally assisted tunneling of heated electrons over a barrier produces a sudden decrease in the drain current (and negative differential resistance in the drain circuit) and a concomitant increase in the substrate current. NERFETs in the GaAs/AlGaAs system fabricated in our lab yield a drain current peak-to-valley ratio of 2. In an effort to improve the switching in this device, a strained layer of InGaAs was placed between the GaAs channel and AlGaAs barrier. This strained layer channel offers the dual advantages of lower effective mass and improved carrier confinement due to the larger band gap discontinuity between InGaAs and AlGaAs. As the In concentration in the channel was increased, the drain current peak-to-valley ratio increased. At an In concentration of 18%, a peak-to-valley ratio of 45 was measured. This is greater than a factor of 20 improvement in the peak-to-valley ratio.

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## WORK UNIT NUMBER 7

TITLE: Computer-Aided Design of High-Performance Integrated Circuits with Ultra-Small Features

### SENIOR INVESTIGATORS:

I. N. Hajj, Research Professor
S. M. Kang, Research Associate Professor
V. B. Rao, Research Assistant Professor

### SCIENTIFIC PERSONNEL AND TITLES:

P. Gee, Research Assistant
T. K. Yu, Research Assistant

### SCIENTIFIC OBJECTIVE:

The continuing evolution of integrated circuit processing technology toward ultra-small feature sizes and new compound semiconductor materials and devices demands new computer-aided design (CAD) tools and design methods. One of the basic issues is to develop efficient circuit models for new devices such as the High-Electron Mobility Transistor (HEMT) and important parasitics of interconnects in high-speed integrated circuits. With such models, integrated circuits can be simulated accurately. During the last two years, we have developed HEMT models and a time-domain circuit model for lossy transmission lines. Our next goal is to develop CAD tools for evaluating the effects of statistical process variations on chip yield, reliability, and design verification of Ultra-/Very-Large Scale Integrated (U/VLSI) circuits. Novel parallel computation algorithms and optimization in view of yield and reliability will also be investigated.

The main objectives of this research unit are:

(1) to develop accelerated circuit simulation methods for U/VLSI circuits by exploiting hierarchy and parallelism; and

(2) to develop rigorous design optimization techniques and programs for yield and reliability enhancement.

### SUMMARY OF RESEARCH:

During the past year, we have explored the parallel implementation of variations of waveform relaxation algorithms for circuit simulation based on the Gauss-Jacobi and the Gauss-Seidel methods. Simplified speedup estimates are used in a presimulation selection procedure that selects the fastest of the parallel waveform relaxation algorithms prior to performing the simulation of a given circuit on a given number of processors. The parallel waveform relaxation algorithms have been implemented in programs that run on an 8-processor Alliant FX/8 multiprocessor computer [2,43].

We have also studied the convergence properties of the Gauss-Seidel and Gauss-Jacobi algorithms and established theorems that help in constructing circuit partitioning algorithms that ensure the convergence of the relaxation process [33].

We have also developed and implemented a dynamic partitioning method based on piecewise-linear device characteristics that produced computational speedups of two orders of magnitude compared to standard circuit simulation. Simulation using the dynamic partitioning method on the Alliant FX/8 multiprocessor computer results in efficient use of the processors and corresponding improvement in speed [7,10].

In another related project, we have developed and implemented parallel circuit simulation algorithms based on the direct method and on nested partitioning techniques to be used in the simulation of circuits containing detailed complex models [30] Computational speedups of up to 7 were obtained using an Alliant FX/8 multiprocessor computer with eight processors.

For very large digital circuits, however, detailed waveform simulation, even when parallel processing is used, may not be cost effective. In many cases, it is not necessary to verify detailed transistor-level operation of a large portion of the design In this regard, we have developed a nonlinear macromodeling approach where a channel-connected subcircuit structure is automatically reduced to a parameterized inverter circuit. The macromodeling approach splits the subcircuit into transistor gate information and loading information. In a given design, many subcircuits have identical gate configurations, but each instance of a gate has a unique RC loading condition. During simulation the gate and loading information are combined and used to calculate output node voltage changes. All necessary information needed for voltage calculations is precomputed and stored in tables. Using the proposed macromodeling and the delay method greatly reduces simulation time. The approach has been implemented in a simulator iDSIM2, and a number of large examples obtained from industry have been simulated. Speedups of up to three orders of magnitude have been obtained compared to standard circuit simulation, with loss of timing accuracy of less than 10% [29,35,42].

For yield enhancement with statistical integrated circuit design, we have developed an efficient method for modeling statistical performances of integrated circuits [3,9,12]. This method can be applied to determine an important subset of device parameters that account for statistical variations in V-I characteristics of transistors. It also provides a concrete guidance on how to determine the number of important parameters. This method is useful in statistical analysis of small circuits, but its direct application to practical VLSI circuits can be limited by the required simulation work load. This method can be used to systematically determine the worst-case, best-case, and medium-case device model parameters that in turn can be used for circuit or switch-level simulations. For statistical analysis of larger circuits, we have built noise arrays using three macrolevels of transistor characteristics. These noise arrays were then combined with control arrays of design parameters to abstract the entire process and design domain. Experimental design techniques were then used to sample a proper subset that can represent the statistical variations in circuit performances due to process variations. We have developed a new technique called Non-Nested Experimental Design (NNED) that requires significantly less computer simulations than the much publicized Taguchi method [3]. An interactive software package called iEDISON was developed to provide statistical design capability [9]. The iEDISON program has been used to improve the yield of both analog and digital circuits with designed-in tolerance of process variability.

In the area of automatic circuit synthesis, we have developed an approach that automatically generates a transistor-circuit netlist from a high-level specification, such as Boolean functions or truth tables. The approach uses switching network logic models and is capable of synthesizing circuits with a minimum number of transistors. The method has been developed and implemented to design both combinational and sequential circuits [13]. A design system has been developed that couples the synthesis approach to a layout system based on the Metal-Metal Matrix ($M^3$) design style [15,17,19]. Thus we are able to automatically generate circuit layout from functional specifications.

In the electrical (or circuit) level design of VLSI circuits, the performance of the circuit could be affected by both circuit as well as process parameters. In digital circuits, the two major factors affecting the performance are the *area* A of the chip, and the *maximum delay* D between a primary input and a primary output in the circuit. The typical critical variables chosen are the widths of the transistors in the circuit, assuming that all the lengths are fixed at the minimum value allowed by the current technology used. There have been several heuristics developed in the past for solving the transistor sizing problem.

In the previous JSEP Annual Progress Report, we reported the development of a tool called iJADE [1], which is a rule-based hierarchical circuit optimizer for CMOS circuits written in Franz

LISP. During the past year, we have developed another technique that solves the optimization problem directly using the Rosenbrock's method of rotating coordinates [20]. In this new technique, a hard constraint is enforced such that all transistor widths lie between a minimum width $W_{min}$ and a maximum width $W_{max}$. The user has the option of choosing one of three objectives:

(a) Minimize delay D subject to $A \leq A_{max}$.

(b) Minimize area A subject to $D \leq Dmax$.

(c) Minimize $AD^p$, where p is a user-defined parameter to weight the delay in the area-delay product. Typical values are p=1 or p=2.

We have tried this new approach on a chain of CMOS inverters driving a capacitive load $C_{load}$. The conventional Mead-Conway design technique suggests that the width of the transistor in the $k^{th}$ inverter be chosen as $W_k = f^k W_1$, where $f>1$ is a scale factor chosen to minimize the overall delay. The transistors sized by our approach, however, exhibit a different pattern. The widths of the transistors fall exponentially in the first few stages, remain constant in the middle, and rise exponentially in the last few stages. This effect is enhanced by increasing $C_{load}$ and increasing the number of stages. Moreover, both the area A and the delay D of the circuit sized by our approach was considerably less than in the circuit sized by the conventional Mead-Conway approach.

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# WORK UNIT NUMBER 24

TITLE: Electronic and Transport Properties of Ultra-Low-Dimensional Structures

## SENIOR INVESTIGATORS:

J. P. Leburton, Research Associate Professor
I. Adesida, Research Assistant Professor
J. Kolodzey, Research Assistant Professor

## SCIENTIFIC PERSONNEL AND TITLES:

S. Boor, Research Assistant
D. Jovanovich, Research Assistant
A. Ketterson, Research Assistant

## SCIENTIFIC OBJECTIVE:

This unit work explores the potential of ultra-low-dimensional semiconductor structures for electronic and optical device applications. The emphasis is placed on fast transient and the research is concerned with the conception, design, and investigation of nonconventional devices characterized by extreme quantization of the electronic system.

Our method involves an integrated theoretical and experimental approach including various technological components from material growth, processing, and testing to numerical simulation of nanostructures. In addition, we are conducting a fundamental investigation of new physical effects in ultra-low-dimensional systems.

## SUMMARY OF RESEARCH:

### Novel FET-Device Configuration and New Injection Mechanism

With partial JSEP support, we have conceived a new device configuration for modulation-doped structures and have proposed a new tunnel injection mechanism into the channel of FET devices. This novel configuration is a generic structure that combines a MODFET with a tunnel junction and can be modified for various device purposes. We have proposed two new 3-terminal devices—the BITFET and the TIFET—that operate with tunnel injection through the homojunction and capitalize on negative differential resistance (NDR) and its modulation by the gate field. Abrupt NDR transitions and large peak-to-valley ratios are anticipated. Theoretical estimates of the relevant time constants indicate frequency operation in the 100 GHz range.

Modulation-doped compound semiconductor layers of two material systems, AlGaAs/GaAs and InAlAs/InGaAs/InP, have been grown by MBE in the laboratory of Dr. A. Y. Cho at AT&T Bell Laboratories and processed into 4-terminal transistors comprising: gate, source, drain. and substrate contacts. Due to the underlying $p^+$ tunnel layer that can undesirably short out the source-to-drain contacts, the ohmic contact process was carefully studied. It was found that rapid thermally annealing of Au/Ge/Ni/Au contacts gives the best results.

For the Schottky barrier gate contacts, we systematically studied three metals (Au, Al and Ti) and found that Ti gives the lowest leakage in the device process steps with a current less than 200 $\mu$A.

To contact the $p^+$ tunnel layer, we etch through the top layers and use Zn/Au metal. The final device contact pads were designed to be compatible with Cascade microwave probes and to permit testing at high frequencies.

On the AlGaAs/GaAs TIFET, initial dc measurements of the drain current $I_D$ versus drain-source voltage $V_{DS}$ characteristics showed much structure, which suggested resonant tunneling into 2-D quantum well subbands.

With this encouraging data we next characterized the InAlAs/InGaAs TIFET, which has a larger conduction band offset and a smaller band gap than the AlGaAs/GaAs version for carrier confinement and tunneling in the active region. An analysis of the drain current versus drain voltage characteristics indicates that tunneling injection from the substrate takes place in the active region, as expected from our model. We are currently analyzing these results to understand more fully the device behavior and to optimize the material structure for high-speed performance. (A patent application has been submitted to the Patent Office for the discovery of the new devices.)

**Investigation of One-dimensional Structures**

*Microstructure and Device Fabrication*

We have established processes for the fabrication of ultra-small structures using electron beam lithography (EBL) and reactive ion etching (RIE). Electron beam lithography utilizing a multilayer resist approach in the Cambridge EBMF 6.5 lithography system (at the Center for Compound Semiconductor Microelectronics) has been developed. To date we have realized isolated metals with linewidth of ~ 100 nm and gratings with the same linewidth dimensions at 200 nm periodicity. During the last year, we have received a Cambridge S360 scanning electron microscope (SEM) that will be utilized as a lithography system to realize structures down to ~ 20 nm dimensions. A computer-controlled pattern generator has been constructed and is currently being interfaced to the SEM.

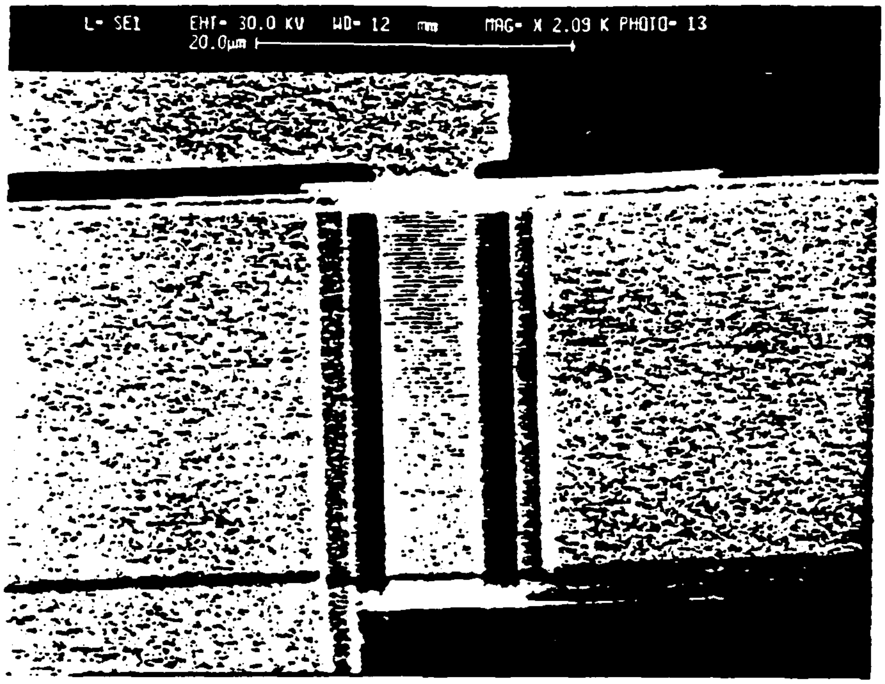
Reactive ion etching of AlGaAs/GaAs heterostructures in $SiCl_4$ and $SiCl_4/SiF_4$ plasmas has been established. Preliminary results have also been obtained for the RIE of InGaAs/InP heterostructures in methane-based plasmas.

As regards device fabrication, major efforts have been expended in setting up various device processing methodologies in our laboratory. Using these techniques along with EBL, we have fabricated high-performance short gatelength modulation-doped FETs in various material systems. In AlAs/InGaAs/InP MODFETs exhibiting unity current gain, cut-off frequency, $f_T$, in excess of 110GHz has been realized. We have started exploratory work on the fabrication of quantum wire FETs (QWFETs) in AlGaAs/GaAs modulation-doped systems. Figure 1a shows half of a device with the discrete channels enlarged in Figure 1b. The physical dimension of the channels is 200 nm linewidth at 600 nm periodicity, and it was realized using EBL and RIE in $SiCl_4/SiF_4$.

*Transport Simulation of Quantum-Wire Structures*

We have investigated the transport properties of multi-subband quasi-one-dimensional systems by a particle Monte Carlo simulation and have found that the transport parameters are a sensitive function of the confinement conditions. For optimum confinement, the 1-D carrier mobility is over twice the bulk value at room temperature. We attribute this excess value to the reduction of the phase-space that enhances the average carrier velocity.

We have also investigated Resonant Inter-Subband (polar) Optic Phonon Scattering (RISOPS), which is similar to magneto-phonon effect. RISOPS is, however, more general than its magnetotransport analog since it occurs with an anisotropic y-z confining potential that results in nondegenerate unequally spaced 1-D energy levels. With a Monte Carlo code that includes up to 20 subbands, we have simulated 1-D transport under RISOPS in various confinement potentials. For all confinement configurations, we have observed velocity oscillations as a function of confinement, similar to magnetophonon effects. In addition, we also predict significant population inversion between subbands at room temperature, even for high-order intersubband-phonon resonance. This effect, which results



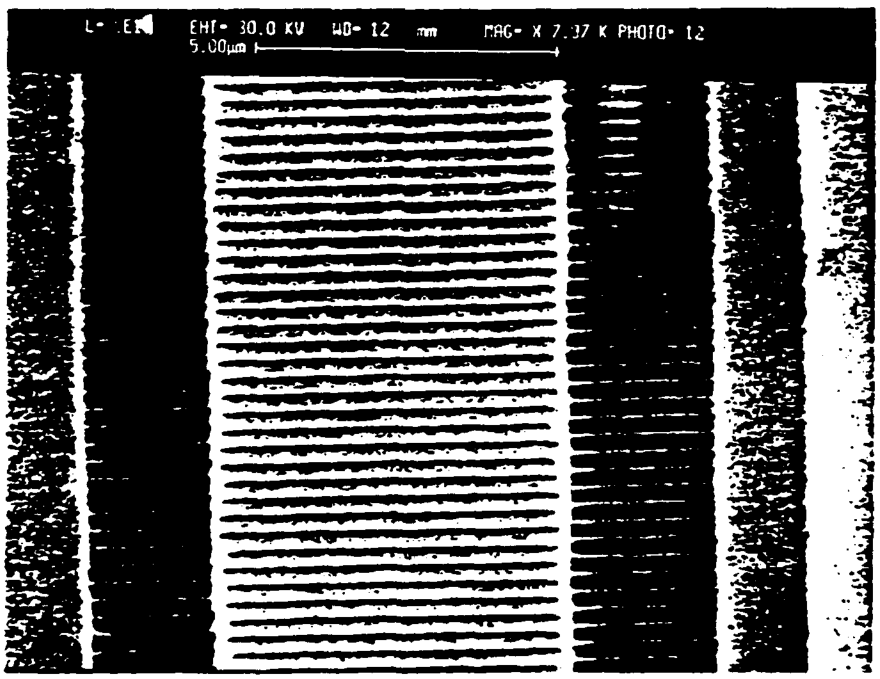




Fig. 1. (a) One-half of a Quantum-wire FET showing in (b) the discrete channels 200nm linewidth at 600 nm periodicity.

from rapid onset of nonlinearities in 1-D transport, seems to be large enough to observe far-infrared stimulated emission in quantum wire structures.

## EXPECTED RESULT/IMPACT

The technology of nanostructures is a fast-growing area. Although not common practice, the fabrication of quantum wire structures is rapidly evolving toward systems of higher confinement. The observation of 1-D effects at temperatures above liquid helium is now perceptible. The prospective of high-performance 1-D devices operating at nitrogen temperatures and above is becoming more realistic. Our effort is providing the basic experimental and theoretical tools for the research in this direction. Some of our recent results already anticipate potential applications of nanostructures in sophisticated device electronics.

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## WORK UNIT NUMBER 8

TITLE: Collective Electronic Transport in Quasi One-Dimensional Systems

SENIOR INVESTIGATORS:

J. R. Tucker, Research Professor
J. W. Lyding, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

W. G. Lyons, Research Assistant

SCIENTIFIC OBJECTIVE:

During the past three years, most of our work under the JSEP program has been directed toward understanding the novel conduction mechanism represented by moving charge density waves (CDWs) in certain quasi one-dimensional metallic crystals. The CDWs in these materials, $NbSe_3$, $TaS_3$, $(TaSe_4)_2I$, $K_{0.3}MoO_3$, and related compounds, form below a Peierls transition temperature $T_P$~100K, and they become depinned from impurities and carry a current above a threshold field $E_T$~0.1V/cm. The response of CDWs to applied electric fields is nonlinear in both field and frequency, and novel electronic devices may become possible if the basic processes in these systems can be understood. The motion of CDWs represents the only known example of collective electronic transport by a moving quantum ground state, apart from superconductivity. Understanding the dynamics of this unique conduction process, therefore, became a subject of great interest to the condensed matter physics community and was regarded as one of the two or three leading problems in this field over the past ten years or so.

SUMMARY OF RESEARCH:

We originally became involved in this area as a result of John Bardeen's proposal [8] that a new type of macroscopic quantum tunneling might provide the basic mechanism for CDW acceleration in an electric field, somewhat by analogy to Zener breakdown across an energy gap in semiconductor p-n junctions. A large number of experiments were performed in our laboratory over the past several years, mostly under JSEP sponsorship, designed to test Bardeen's ideas. Initially, there appeared to be some nontrivial correspondences between our experimental findings and theoretical expectations based upon the tunneling hypothesis. As more features of the extremely complex dynamics were revealed here and elsewhere, however, it became clear that the tunneling model could not possibly describe the entire observed range of behavior without some major extensions and/or revisions. Furthermore, our concerted efforts to find a firm theoretical basis for this novel type of macroscopic quantum tunneling ultimately proved unsatisfactory (we therefore withdrew that work shortly before its scheduled publication).

Two years ago, we began examining the theoretical alternatives again from scratch and realized that a significant possibility had been overlooked, due to a mistake made years ago that had then been codified into the conventional wisdom of the field. Since about 1980, it has been known that the phase of the CDW must be correlated over volumes much larger than the average volume $1/n_i$ associated with an individual impurity ($n_i$ represents their density), through electron microscope images of the satellite diffraction spots, and also by indirect inference from other experiments. These results led everyone to believe that the impurity pinning was weak, in the sense that the CDW phase

is not pinned to its optimum value at each impurity site but adjusts itself to fluctuations in the total impurity potential over some much larger volume. All subsequent theoretical proposals were thus based upon the concept of weak pinning as originally outlined by Lee and Rice [9], including the Bardeen tunneling model. What was not appreciated was that the same paper by Lee and Rice also contained a Ginzburg-Landau characterization of a single strong impurity, which showed that the CDW phase would only be deformed from its value at infinity within a tiny region immediately surrounding the impurity site in three dimensions. We subsequently demonstrated that when many strong impurities are present, the large- scale average phase will remain correlated over volumes much greater than $1/n_i$, so long as these tiny phase-adjustment regions surrounding each impurity site do not overlap (which occurs only at enormously large densities). This large-scale average phase is then in effect weakly pinned by the impurities, even though the local CDW phase is pinned strongly at each impurity site.

Once this crucial idea was appreciated, the process of developing a theoretical model proceeded rapidly. Essentially all known aspects of CDW dynamics were found to fit well within such a framework, and quantitative estimates made on this basis proved surprisingly accurate. With considerable regret, we were forced to pursue this set of ideas as the simplest and most coherent explanation for the complex dynamics of CDW systems. Professor Bardeen took great exception to these efforts and has chosen to disassociate himself entirely from our research group.

Our basic ideas on a strong pinning theory were published this past year in a rather lengthy paper [3] . In it, we attempted to quantitatively interpret most of the basic transport phenomena that had been observed in sliding CDW systems over the past decade. This long paper was actually preceded in publication by a *Phys. Rev. Letter* [1] that showed how apparently conflicting NMR experiments on CDW systems could be consistently interpreted. Later on in the year, we found additional striking correspondences with more recent experimental data, and two Rapid Communications were published. The first [4] showed how the strong-pinning model successfully predicts the entire ac excitation spectrum for pinned CDWs, with accurate values for all three observed conductivity resonances. The second [5] showed how all of the unique features seen at very low temperatures can also be understood in terms of this model, including an accurate quantitative estimate for the second depinning threshold.

We are quite certain that we have finally solved the basic problem of CDW dynamics, although the politics of this field remains as vicious as ever. Most recently, we have succeeded in integrating the microscopic characterization of impurity pinning due to Tutto and Zawadowski [10] within the large-scale Ginzburg-Landau framework. This analysis demonstrates that the pinning is indeed strong in the sense that we have proposed, for any remotely reasonable choice of scattering parameters. We are additionally organizing some of our more recent experimental data, which show the detailed systematics of the ac response. Although we are successfully ending this aspect of our research under the JSEP program, we note that the revolutionary new macroscopic quantum tunneling mechanism that we had hoped to explore apparently does not exist.

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# WORK UNIT NUMBER 9

TITLE: An Investigation of Plasma and Chemistry Processes in Cylindrical Magnetron Plasma Discharges

## SENIOR INVESTIGATORS:

M. J. Kushner, Associate Professor
J. A. Thornton (Deceased), Research Professor

## SCIENTIFIC PERSONNEL AND TITLES:

G. Y. Yeom, Research Assistant

## SCIENTIFIC OBJECTIVE:

The objectives of this program were to investigate fundamental plasma and chemistry processes in cylindrical radio frequency (rf) magnetron discharges and to demonstrate their utility in etching silicon compounds. This type of discharge was initially investigated because of its potential to reduce damage of processed materials by ion impact while maintaining high etching rates.

This research program has completed the following specific objectives:

(1) The basic plasma behavior of rf-driven cylindrical magnetron discharges has been investigated and the delivery of activation energy from the plasma to processing surfaces has been characterized.

(2) The plasma chemistry of low pressure rf-driven magnetron etching plasmas using $CF_4$, $CH_4$–$H_2$, and $CHF_3$ has been examined.

(3) The magnetron reactive ion etching of Si with particular emphasis on the damage mechanisms and on the basic surface chemistry that establishes selectivity and anisotropic etching has been investigated.

(4) The applicability of these discharges to plasma etching has been demonstrated by etching Si and $SiO_2$ with feature sizes $< 1000$Å at rates of $\gtrsim 2500$Å/min with virtually no damage.

## SUMMARY OF RESEARCH:

The construction and characterization of the experimental apparatus was completed in the second year. The characterization of the apparatus with respect to etching of Si and $SiO_2$ was completed during the current year. The experimental apparatus is a plasma discharge chamber having a cylindrical central electrode, which may be of user selected diameter, and a cylindrical housing that serves as the outer electrode. Standard high vacuum systems are used for gas supply and exhaust. The discharge is excited by either dc or rf (1.8 MHz, 13.56 MHz) power supplies and is sustained in a dc magnetic field generated by external coils. The magnetic field (0-250 Gauss) is uniform to within 10% throughout the discharge chamber. The plasma was characterized using (1) electrostatic probe measurements of the plasma and floating potentials, plasma density, and electron temperature; (2) retarding grid electrostatic analyzer to measure ion energies incident on surfaces; (3) optical emission spectroscopy to assess the rate of electron impact excitation; and (4) mass spectroscopy of the species produced in the plasma.

We have found that rf cylindrical magnetron discharges (CMD's) do not, in general, obey the same current-voltage relationships, as do dc magnetron discharges, and appear more resistive. Magnetron discharges are usually characterized by $I \sim V^n$, and rf CMD's generally have lower n. By measuring the potential distribution in the plasma using electrical probes, we have determined that this behavior results from the discharge losing its ability to confine electrons in the magnetron "trap"

on the anodic part of the cycle. In fact, the discharge may not be self-sustaining during the anodic half cycles. In spite of these conditions, though, rf CMD's still maintain the highly desirable feature of developing a low dc self bias on the electrodes and, therefore, will not be as damaging to electronic material being processed as conventional rf diode discharges.

Electrical probe measurements of plasma density have been performed as a function of position in the discharge chamber, rf power, and applied magnetic field to determine the manner of power deposition. As expected, we found that the plasma density increases with increasing magnetic field, an indication of more efficient electron trapping. We also found that the spatial distribution of plasma density shifts toward the inner electrode with increasing magnetic field. These results correlate with our observations of lower dc self bias at higher magnetic fields and indicate fewer highly energetic electrons.

We have completed studies where our rf CMD was used to etch Si and $SiO_2$ using $CF_4$, $CF_4/H_2$, and $CHF_3$ mixtures. We have obtained high etch rates (1000's Å/min) and found that the selectivity of the etch is a function of the applied magnetic field; higher selectivity is obtained with higher magnetic fields. Optical emission spectroscopy, actinometry, and electrical probe measurements have been performed to determine the relative rates of excitation, ionization, and fragmentation.

We found that the F atom density and ion densities monotonically increase with increasing magnetic field strength while the dc bias monotonically decreases. The etch rates, though, optimize at an intermediate value of magnetic field corresponding to a dc bias of $\approx$50V. The polymer layer on the surface of the wafer was a minimum at that value of magnetic field. These results indicate that a minimum dc bias is required to provide energetic ions to activate the etching process; higher radical and ion densities are ineffective below this bias. Wafers etched at the optimum conditions showed negligible damage when examined using TEM and Schottky diode characterization.

Using electron beam lithography to apply fine line masks, feature sizes of $\lesssim$750Å were etched at rates of $\gtrsim$2500Å/S in both Si and $SiO_2$ using our rf CMD.

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## WORK UNIT NUMBER 10

**TITLE:** Excited State Chemistry in Gases

**SENIOR INVESTIGATORS:**

J. G. Eden, Research Professor
J. T. Verdeyen, Research Professor

**SCIENTIFIC PERSONNEL AND TITLES:**

C. C. Abele, Research Assistant
C. J. Kiely, Postdoctoral Research Associate
L. Overzet, Research Assistant

**SCIENTIFIC OBJECTIVE:**

Excited states and/or free radicals, produced by a gas discharge or an intense laser beam, play a critical role in the etching and deposition of semiconductor material. One case, dry processing with plasmas, has become the "standard" industrial tool, and much of the imaginations involving laser interactions are beginning to bear fruit. Inasmuch as these sources of radicals and excited states produce an environment that is far from that described by equilibrium thermodynamics, one can expect unique, puzzling, and yet most interesting processes resulting from the use of these techniques. Our goals have been and continue to be the understanding of the complex processes responsible for those actions and a development of a scientific model that quantifies the interaction between the source (electrons or photons), the donor gas, and the semiconductor surface. We will continue the basic study of the kinetic processes occurring in these environments, but we also plan to combine the two technologies.

To gain further insight into these complex processes, a specific target for this next period is to combine the discharge, with its ability to produce copious quantities of free radicals in almost anything rather easily, with the laser, which has the advantage of energy selectivity and directionality.

**SUMMARY OF RESEARCH:**

**Metal Ion Production by Multiphoton Ionization of Molecules**

Our emphasis in the past year has been placed on exploring multiphoton processes in metal-halide or metal-alkyl molecules that allow one to efficiently and selectively produce singly-charged metal ions. Little work has been done in this area, but this approach has (we believe) considerable promise as a means of generating intense beams of ions for implantation or III-V film growth. Current methods for producing ions are generally inefficient and a wide range of ions are often produced that then must be mass resolved. A much less expensive and efficient approach is to generate such species optically.

Last year at this time we had completed initial studies of the fragmentation of trimethylgallium (TMG) by a blue dye laser beam. Since then, we have focussed on the metal halides (such as InI) for several reasons:

(1) The halides are available commercially at higher purities than are those for the alkyls;

(2) The molecular structure for the diatomic monohalides (or the trihalides) is considerably simpler than that for the larger alkyls. Consequently, one has much more control with the halides over the product channels (i.e., there are considerably fewer exit channels available with the halide molecules);

(3) The existence of an ion pair state (i.e., $M^+X^-$, where $M^+$ and $X^-$ are metal and halogen atomic ions, respectively) offers an ideal opportunity to produce only <u>one</u> positive ion, the metal atom.

Because of these considerations, our efforts have focussed on the InI molecule and an extensive laser spectroscopy program has been undertaken to examine its structure in detail. Surprisingly, little has been done in the past to characterize the excited states of the molecule. This program has been quite productive as evidenced by the following:

(1) The excited A and B states of the molecule have been thoroughly characterized and their asymptotic limits determined. (These states act as "platforms" for the final ionization process.)

(2) Photoionization spectroscopy of the molecule in a proportional counter arrangement has clearly shown that $In^+$–$I^-$ pairs can be readily produced by multiphoton absorption in the blue.

As an example, Figure 1 shows the multiphoton ionization spectrum of InI that was acquired in the 402-411 nm region. The sharp peaks at 404.54 and 404.77 nm are attributed to $In^+$–$I^-$ production and represent the resonant enhancement of the ion production rate. The spectroscopic experiments are now nearly completed and the analysis of the spectra will be finished this summer. It is expected that the conclusions reached for the indium-halides will be generally applicable to the generation of all of the column IIIA metal atoms that are of optoelectronic device interest.

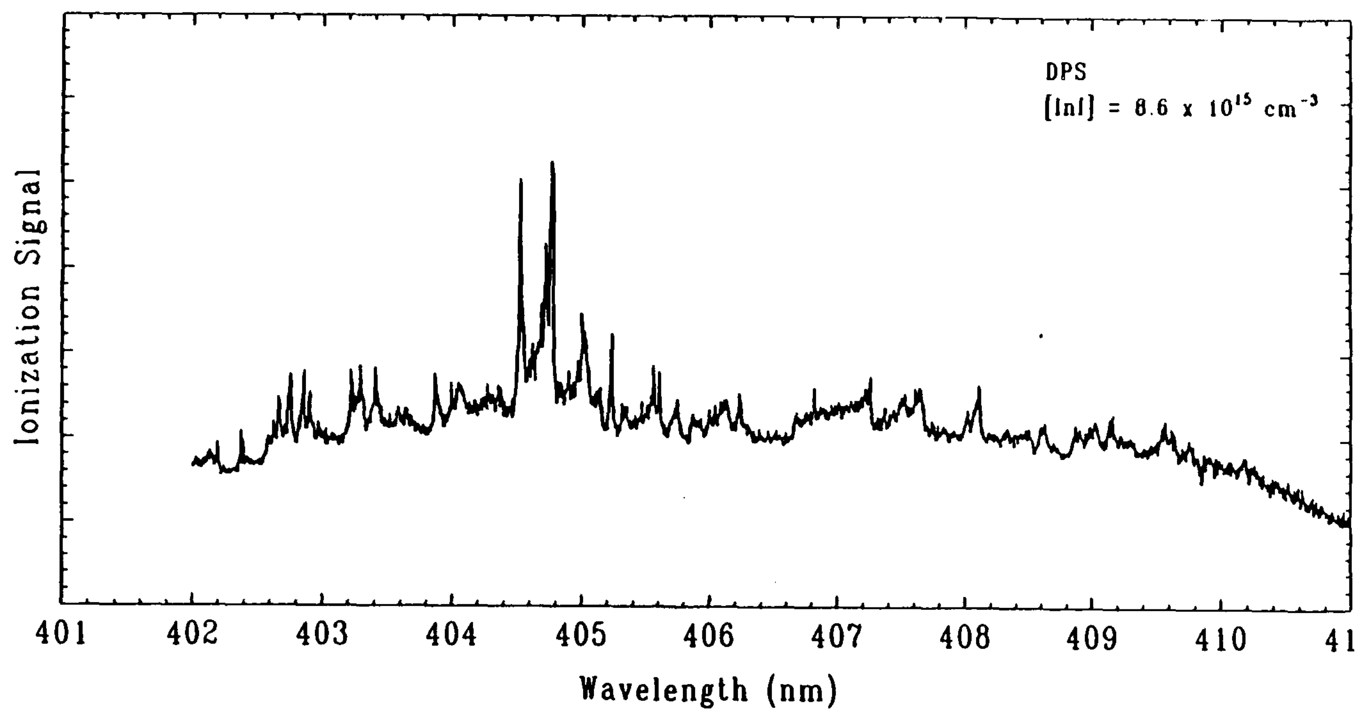


Fig. 1. Multiphoton ionization spectrum of indium iodide in the range of laser dye diphenyl stilbene (DPS). Enhancement in the ionization rate occurs when the wavelength is the same as a transition between the ground state and either the A or B excited states.

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## WORK UNIT NUMBER 11

**TITLE:** Monolithic Millimeter-Wave Integrated Circuits with Microstrip Antennas

**SENIOR INVESTIGATORS:**

S. L. Chuang, Associate Professor
Y. T. Lo, Research Professor

**SCIENTIFIC PERSONNEL AND TITLES:**

M. I. Aksun, Research Assistant
S. M. Lee, Research Assistant

**SCIENTIFIC OBJECTIVE:**

The principle objective is to investigate the monolithic integration of microstrip antennas with microwave integrated circuits. This requires the judicious choice of a feed structure that is suitable for monolithic microwave integrated circuits (MMIC) and the study of antenna performance using the proposed novel feed configuration.

**SUMMARY OF RESEARCH:**

We have successfully demonstrated both theoretically and experimentally, **for the first time**, the design of circular-polarization (CP) of microstrip antennas using electromagnetically coupled feeds including slot feed, aperture-coupled feed, and coplanar waveguide feed. These feeds are planar structures and are suitable for the monolithic integration purpose. Our theoretical results agree very well with the experimental data as discussed below. We believe our accomplishments will have significant impact on the future designs of microstrip antennas for monolithic millimeter-wave integrated circuits. These feed structures for circular polarization operation of microstrip antennas are new:

**(a) Study on Slot-Coupled Microstrip Antennas**

We have derived the design formulas for the circular-polarization operation of microstrip antennas for slot feeds using the cavity model. These formulas were used to design an arbitrarily oriented slot-fed microstrip antenna with various substrate thickness, and the CP performances were measured experimentally. Since the input impedance of a microstrip antenna is a very important parameter in the design of monolithic integrated circuit, it has been studied theoretically for slot-fed microstrip antennas and compared with experiments. Figure 1 shows that the antenna input impedance as predicted from this theory is in excellent agreement with experimental results. A typical result for a CP microstrip antenna on a 1/8" thick substrate is shown in Figure 2. No phase shifters are required in this design. It should be noted that the axial ratio is much lower than 3 dB over a wide range of observation angles.

The CP operation of double-slot fed microstrip antennas has also been studied as an extension to the single slot-fed case. For the experimental investigation, both square and rectangular patches with a double-slot feed were designed and tested, based on this theory. For a square patch with a dual slot feed, a 90° phase shifter must be used.

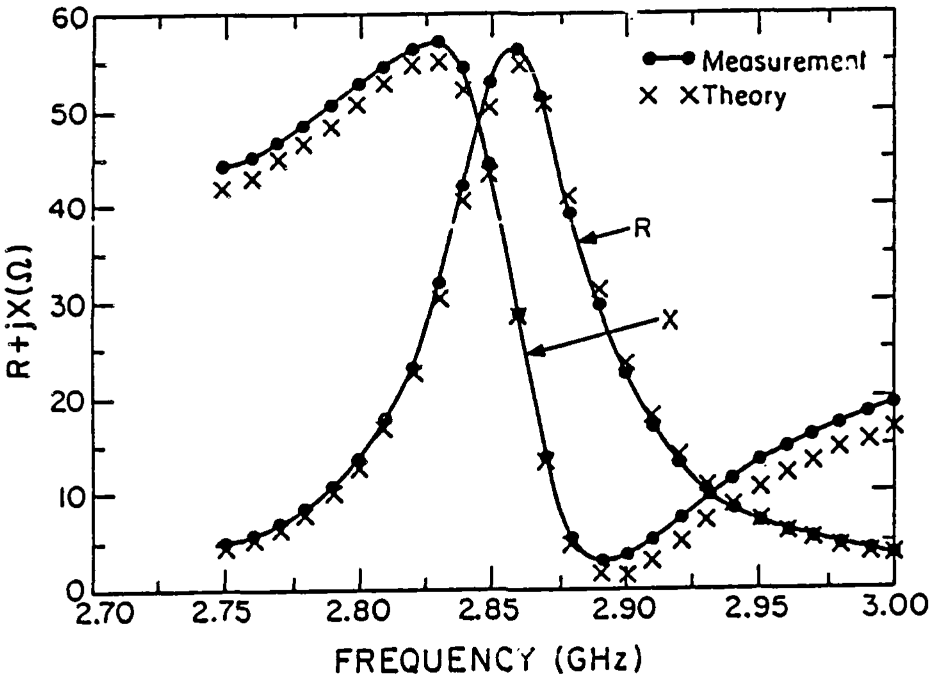


Fig. 1. The input impedance vs. frequency plot of a slot-fed rectangular microstrip antenna.

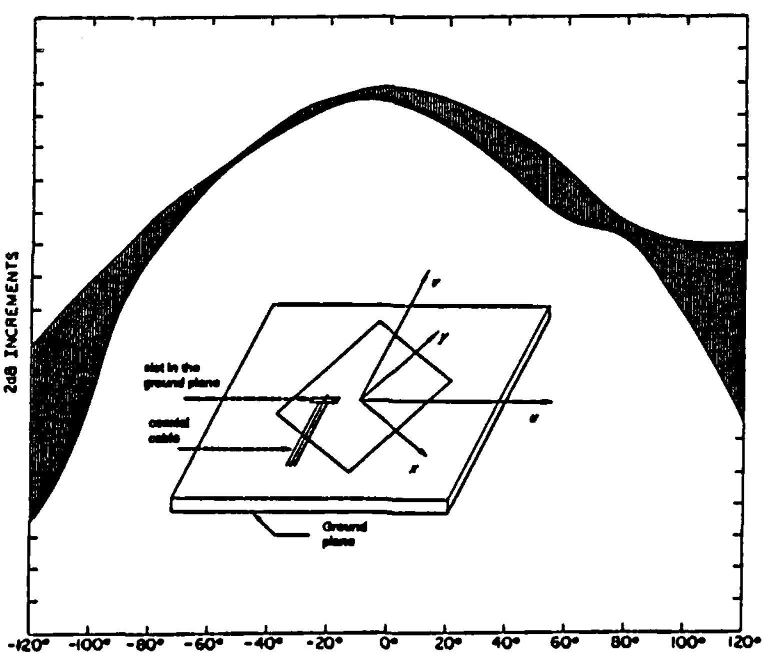


Fig. 2. Radiation pattern for RHCP slot-fed antenna on a 1/8" thick substrate.

### (b) Microstrip Line-Fed Slot Antennas (Figure 3)

A feed structure consisting of microstrip lines and slots is a very attractive system to excite a large planar antenna array. It is important to understand some of its features such as surface waves, input impedance, and the effect of microstrip line stubs and superstrates to antenna performance. Some of these properties cannot be analyzed with the cavity model theory; therefore, the method of moments, in particular, in the spectral domain must be used.

This problem has been solved in three steps: the calculation of (1) the propagation constant of the microstrip line, (2) the reflection coefficient of an infinite microstrip line-fed slot antenna, and (3) the reflection coefficient of an open-end microstrip line. Consequently, the reflection coefficient, in turn the input impedance of the microstrip line-fed slot antenna, is obtained by the use of a multiple reflection scheme. The advantage of this formulation is that once (1) and (2) are calculated, changes in the length of the microstrip stub do not require the calculation of (1) and (2) again. Therefore, the effect of the stub to the input impedance can be investigated with almost no need for extra computation time.

### (c) Coplanar Waveguide-Fed Microstrip Antennas (Figure 4)

Coplanar waveguide has a number of advantages in the monolithic integrated circuits: (1) low radiation leakage that allows circuit elements to be placed close to each other, (2) planar construction that allows shunt and series connections with ease and without using via holes, (3) the availability of high Q for the simulation of lumped elements, and (4) flexibility of geometrical dimensions while maintaining a constant characteristic impedance. A possible configuration for using coplanar waveguide to feed a patch antenna is shown in Figure 4. This structure has been studied by the method of moments in the spectral domain.

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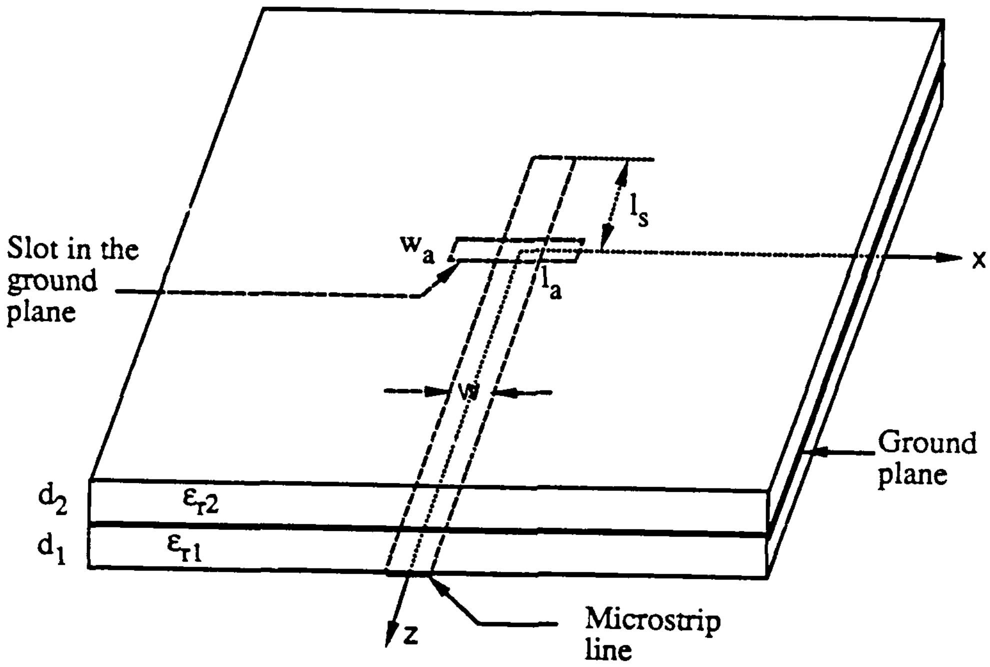


Fig. 3. Geometry of a microstrip line-fed slot antenna.

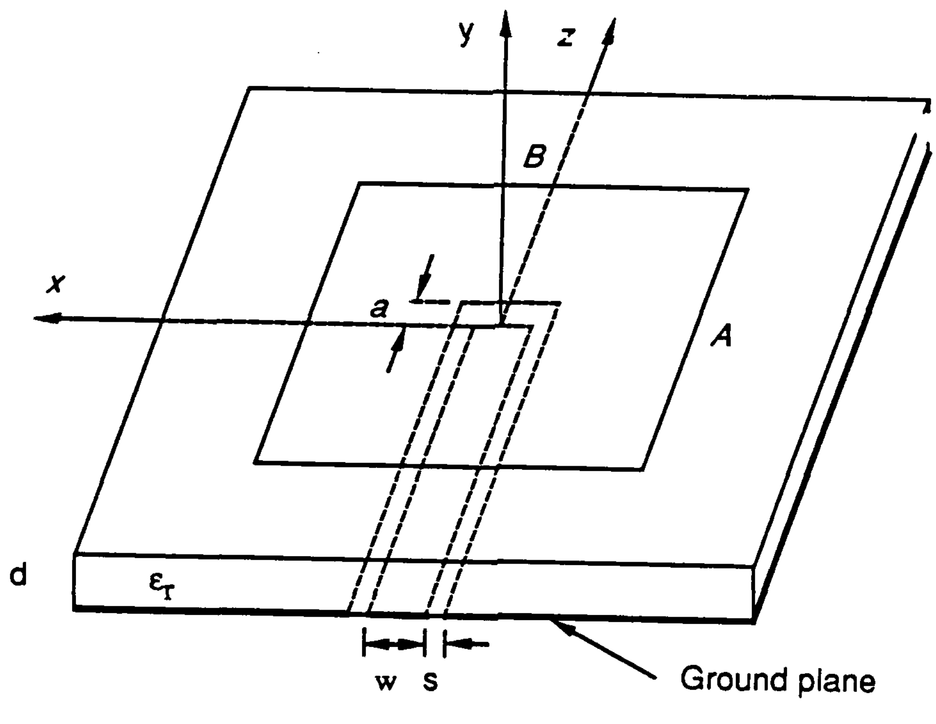


Fig. 4. Geometry of a coplanar waveguide-fed microstrip antenna.

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## WORK UNIT NUMBER 12

TITLE: Investigation of Radar Scattering Characteristics of Controllable Surface Shapes with Application to Low Observable Targets

### SENIOR INVESTIGATOR:

R. Mittra, Research Professor

### SCIENTIFIC PERSONNEL AND TITLES:

A. Peterson, Visiting Assistant Professor
C. Chan, Visiting Assistant Professor
A. Chang, Graduate Student
R. Gordon, Fellow
R. Jorgenson, Graduate Student
J. Joseph, Graduate Student
K. Merewether, Fellow

### SCIENTIFIC OBJECTIVE:

*There are three principal objectives of this effort.* The first is to develop efficient integral equation and differential equation techniques for solving the problems of electromagnetic scattering and coupling into complex structures. The second is to study techniques for reducing the radar cross-section of targets of different shapes. The third is to analyze frequency selective surfaces (FSS) for radomes and other antenna applications.

### SUMMARY OF RESEARCH:

During the last twelve months we have completed the analysis of resistive honeycombs that are employed in low RCS vehicles. We have developed a method for analyzing honeycomb structures for different orientation of these structures and for different polarizations of the incident field.

For honeycomb slabs of finite thickness, we have employed two different techniques. The first of these is based upon the conventional moment method type of solution, adapted to the special case of the honeycomb geometry. The second one is a generalization of the MoM approach and is useful for thick slabs that require a large number of unknowns. In the second approach, we use special basis functions that correspond to quasi-modes of the hexagonal waveguides with lossy walls. The use of these basis functions enables us to solve the thick slab problem with a relatively few unknowns.

We have considered the problem of radar scattering by a body of revolution, with or without a coating by layered media. Our previous work has now been generalized to the case of a partial coating, i.e., where only a portion of the body is covered by one or more dielectric layers.

We have developed new Absorbing Boundary conditions (ABCs) that allow one to truncate a Finite Difference (FD) or Finite Element (FEM) mesh at distances that are not far from a scatterer. The use of the ABCs enables one to reduce the number of grid points substantially when solving open region scattering problems.

We have investigated the effects of truncating a frequency selective surface (FSS) on its scattering characteristics. We have also analyzed the problem of interaction of an antenna with an FSS

when the two are in close proximity of each other. The interaction of the antenna with the FSS can introduce distortion of its pattern and the modification of its input impedance.

We have initiated a study of FSS loaded with devices whose characteristics can be modified by a modulating signal. The reflection characteristics of the FSS can be changed substantially in this manner and its RCS characteristics can be altered.

We have initiated a study on the use of computers with moderately parallel (JPL hypercube) or massive parallel (Connection machine) for the solution of electromagnetic scattering problems both in the frequency and in the time domain.

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# WORK UNIT NUMBER 13

TITLE: High-Performance Testable Electronic Systems

## SENIOR INVESTIGATORS:

J. A. Abraham, Research Professor
J. H. Patel, Research Professor

## SCIENTIFIC PERSONNEL AND TITLES:

J. Fu, Graduate Research Assistant
C. Gura, Graduate Research Assistant

## SCIENTIFIC OBJECTIVE:

This unit seeks to develop, model, and analyze efficient, high-performance, and testable computer architectures that will exploit compound semiconductor technology. There has been increasing interest in the use of compound semiconductor technologies, such as gallium arsenide (GaAs), as a vehicle to develop high-performance electronic systems. Various studies have indicated that GaAs devices will become a larger share of the semiconductor market in the coming years. In addition to the high performance possible, the capability for greater radiation hardness in the compound semiconductor technology is of great interest to military systems. We have identified several aspects of computer architecture for particular attention, due both to their emerging importance from a technology-driven point of view and to the lack of known structures or analysis techniques for meeting our objective.

## SUMMARY OF RESEARCH:

### Memory Organizations

Trace-driven simulation is a simple methodology for evaluating cache memory systems with varying hardware parameters. It is generally agreed that to obtain creditable cache behavior, realistic workloads with several million addresses are necessary. Unfortunately, such large-scale simulation is usually impractical from the consideration of space and time requirements. The goal of this research is not to simply report more simulation results for cache memories, but to develop new methods for cache simulation based on statistical techniques that will decrease the need for large address traces and yet predict true program and cache behavior.

In the proposed method, sampling techniques are applied while collecting the address trace from a workload. The cost of the sampling-based simulation method, in terms of both memory space and computer time, is significantly lower than conventional techniques. For a trace length of say 100 million references, the sampling-based method typically requires collection of only 3% or less of the trace. The data from simulation of samples were analyzed and modified to give a good estimate of the miss ratio. A new concept of "primed cache" was introduced to simulate large caches by the sampling-based method. This was achieved by simulating only those portions of the cache whose true state can be recreated even from the sampled trace. Extensive verification experiments were carried out, and the results obtained indicate that the primed cache concept combined with sampled address simulation gives very accurate miss rates.

Our earlier work focused on single processor non-numeric workloads. In the past year, we have started to apply trace-sampling methodology to a multi-processor environment executing numerical

workloads The current multi-processor model has eight processors with private caches and usees a simple write-through algorithm for maintaining cache coherence. Parallel and vectorized traces are generated through an emulation of the Alliant FX/8 multi-processor. The workload includes benchmarks from the "Perfect Club" such as ARC3D and SPICE. The benchmarks generate between 30-300 million references each in execution.

Initial experiments have been performed using cache sizes up to 128 Kbytes and set associativity from 1 to 4. The experiments compared the individual and average cache miss rates of the caches for the full trace and a much smaller sampled trace for a benchmark. The results indicate that using a sample size of about 100,000 references and taking a number of samples (about 30 to 40) predicts the miss ratio very accurately, with a relative error of less than 5% in most cases. In the future, this work will also include the effects of multiprocessor cache coherence.

**Circuit and Packaging Technology**

In this research we considered a combination of packaging, device technology, and chip density that yields the optimum system performance. The performance of a packaged system depends on device technology, packaging technology, system architecture, and logic partitioning. We studied the four major aspects of the problem: logic partitioning, system size, interconnect and device delay, and the average interconnection length. It is possible to characterize a system as a hierarchical set of packages, each package level being composed of blocks or packages from the lower packaging level. Previously, it had been shown that it is possible to link the architecture to the packaging characteristics through the use of the the Rent's rule, which relates the number of terminals on a block to the block size. We have shown that it is possible to link the architecture to the packaging through a set of hierarchical terminal-block relationships. Hierarchical terminal-block relationships capture aspects of the system design that are not captured by Rent's rule.

The high-speed characteristics of interconnections and packaging are needed to reliably evaluate future technologies and packaging alternatives. In this context, we have developed new techniques for simulating lossy (RLC) transmission lines based on the method of characteristics. For uncoupled lossy transmission lines, we have developed a method that speeds up the simulation time by a factor of two compared with existing techniques. A method is also presented for the transient analysis of coupled lossy lines in an inhomogeneous medium. Previously, simulation techniques were limited to coupled lossy lines in a homogeneous medium.

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## WORK UNIT NUMBER 14

**TITLE:** New Directions in Fault-Tolerant Computing

**SENIOR INVESTIGATORS:**

P. Banerjee, Research Assistant Professor
W. K. Fuchs, Research Assistant Professor
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**SCIENTIFIC PERSONNEL AND TITLES:**

S. Patil, Research Assistant
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S. Subramani, Research Assistant

**SCIENTIFIC OBJECTIVE:**

This unit is concerned with exploring new directions in fault-tolerant computing that will be useful in understanding the basic principles in design, testing, error prediction, and circumvention for reliable complex computer systems. Basic research is being performed in the three areas of parallel test pattern generation, reliable distributed database systems for real-time applications, and intelligent error prediction and circumvention.

**SUMMARY OF RESEARCH:**

### Parallel Algorithms for Automatic Test Generation

In the past year, we designed a parallel test generation system for combinational circuits called HIPERTEST. The parallel algorithm has been implemented on an Intel *i*PSC/2 hypercube multiprocessor. We identified the problems inherent in a uniprocessor implementation of a test generation algorithm and investigated methods to remedy these problems by parallel processing. The parallel test generation is divided into two phases. The first phase uses independent test generation/fault simulation and the second phase uses parallel search for hard-to-detect faults.

During the first phase, all processors perform test generation and fault simulation independent of each other. We proposed a number of heuristics for partitioning faults so that the overall run time and test length is reduced. Also, a dynamic load balancing strategy requiring a very low communication overhead was proposed. The first phase uses a very low backtrack limit (typically about 25). We were able to obtain almost linear speedups during this phase. The faults for which test generation was aborted during the first phase are classified as hard-to-detect (HTD) faults. The HTD faults collected at the end of the first phase are used as inputs to the second phase. The second phase uses a parallel branch and bound algorithm to generate tests for the HTD faults. In this phase, all processors cooperate in generating a test for a single fault. It was shown that this method is able to overcome the deficiencies of approximate testability measures used during test generation and is able to generate tests for faults that are aborted by the uniprocessor algorithm even with a very high backtrack limit. It was shown that not only does the parallel search method result in substantial speedups, it is also able to improve the quality of the solution. Due to search anomalies inherent in any parallel search method, sometimes speedups in excess of the number of processors were obtained. It was shown that parallel processing is a very effective and powerful method to speed up test

generation for logic circuits by orders of magnitude. Currently, we are investigating techniques to speed up test generation for sequential circuits using parallel processing.

**Reliable Distributed Database Systems**

We have completed an experimental study of our new robust storage reclamation algorithms for distributed object-oriented systems. The distributed garbage collection algorithm, which does not require global state information, has been implemented and experimentally evaluated. The algorithm exhibits the property of graceful degradation and functions in the presence of inactive processor nodes. Compaction of objects is supported and object locality is exploited to reduce overhead. The implementation has demonstrated that our approach to distributed garbage collection requires significantly fewer message exchanges between nodes than alternative mark-and-sweep and reference counting algorithms.

In the last year, we have initiated research into compiler-assisted strategies for checkpointing and recovery in message-passing parallel architectures. We have completed the initial implementation of a modified GNU C compiler for automatically determining optimal checkpointing frequencies and checkpoint placement in C programs. We have also developed a technique for graceful degradation in hypercube architectures through data redistribution. The data redistribution technique allows for the CPU-bound programs to execute on groups of cubes of various sizes to achieve graceful degradation without recompilation. The approach has been implemented and evaluated for a suite of parallel programs.

**Intelligent Error Prediction and Circumvention**

In the previous years, we have investigated new methods for evaluating the performability of complex computer systems in conjunction with their operating environment, using real data from different systems. This research has resulted in the development of effective analysis tools for the statistical analysis and interpretation of measured error and performance data. Some examples of this include the generation of statistical distributions for different parameters, the identification of behavioral models using statistical pattern recognition methods, e.g., cluster analysis. In particular, we have developed efficient methods to use measured hardware and software performance and error data to identify appropriate models of a system and its environment. Our work was not only the first to explicitly quantify the impact of system activity on computer hardware and software failures, but it was also the first to derive a semi-Markov model for this dependency from real data. Experiments have been conducted in the use of such models for failure prediction and diagnosis. Apart from analyzing large mainframes like the IBM 3081, this approach has also been used to investigate various reliability and performance issues on the CEDAR multi-computer shared memory system being built at the University of Illinois. In the past year, the validity of this type of approach was further investigated using measured error data from a VAX-Cluster of seven systems.

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## WORK UNIT NUMBER 15

TITLE: Efficient Computation Techniques

SENIOR INVESTIGATORS:

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M. C. Loui, Research Associate Professor
F. P. Preparata, Research Professor
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S. Maddila, Research Assistant
M. L. Prastein, Research Assistant
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D. Zhon, Research Assistant

SCIENTIFIC OBJECTIVE:

For several years one of the most vigorous areas of research in information processing has been the analysis and design of efficient computation techniques. Its impact has been not only on the availability of better computational methods for a number of significant applications, but also on the awareness in the computing community of the crucial importance of algorithmic design. By investigating both upper and lower bounds to the resource requirements of specific applications, this discipline effectively develops a methodology aiming at a quantitative formulation of the inherent difficulty of problems in the appropriate computation models.

The involvement of our research group with this topic is well established and dates back to the early seventies. Our record over this period shows that our focus (as well as that of our peer community) has been adjusting dynamically, as changes in technologies have modified the general research horizon and the perception of relevance. The most significant change of this type has been the advent of Very-Large-Scale-Integration (VLSI), which has profoundly influenced essentially every facet of our current research interests. The advent of VLSI is important in two major respects: one is the present possibility to realize massively parallel computers; the other is the introduction of criteria of complexity (the VLSI "model"), which takes into account the design rules dictated by the new technology. Therefore, while maintaining our interest for problems in the more traditional areas (Von Neumann computations), our current work emphasizes research on the potentially revolutionary domain of concurrent computation.

SUMMARY OF RESEARCH:

During the first two years of the current JSEP contract, we determined that adding multiplication or shift operations to a parallel random access machine (PRAM) individually does not substantially increase its power. Let PRAM[S] denote a PRAM augmented with the set S of unit-cost operations, where $S \subseteq \{*,\uparrow,\downarrow\}$ (multiplication, left shift, right shift). Let PRAM[S]-PTIME denote the class of languages accepted by PRAM[S] machines in polynomial time. Since April 1988, we have proved the astonishing result that PRAM[$*,\uparrow,\downarrow$]-PTIME includes NEXPTIME, the class of languages

accepted by nondeterministic Turing machines in time $O(2^{p(n)})$ for some polynomial p. Since it is widely believed that NEXPTIME strictly includes PSPACE = PRAM[*]-PTIME = PRAM[↑,↓]-PTIME, it appears that the PRAM[*,↑,↓] with both multiplication and shifts is significantly more powerful than the PRAM[*] and the PRAM[↑,↓].

We have also established time bounds for a sequential RAM[S] to simulate a parallel PRAM[S]. Every PRAM[*] of time complexity T(n) can be simulated by a RAM[*] in time $O(T^2(n))$, and every PRAM[↑,↓] of time complexity T(n) can be simulated by a RAM[↑,↓] in time $O(T^3(n))$. Our proofs introduce new concepts of uniformity for circuit families.

We shall present these results at the Structure in Complexity Theory Conference in Eugene, Oregon, in June 1989, and we are preparing two papers on these results for journal submission.

Over the years, we have investigated a number of problems in Computational Geometry that occur in several applied areas. Recently, we have undertaken a systematic study of dynamic point locations, in a variety of settings. Point location is a fundamental primitive in Computational Geometry. In the plane it is stated as follows: Given a subdivision R of the plane and a query point q, determine the region of R containing q. Most of the heretofore results concern the static mode of operation; recently, we have proposed a dynamic technique for locating a point in a monotone planar subdivision, whose current number of vertices is n. The (complete set of) update operations are insertion of a point on an edge and of a chain of edges between two vertices, and their reverse operations. The data structure uses space O(n). The query time is $O(\log^2 n)$, the time for insertion/deletion of a point is O(logn), and the time for insertion/deletion of a chain with k edges is $O(\log^2 n+k)$, all worst-case. The technique is conceptually a special case of the chain method of Lee and Preparata and uses the same query algorithm. We have also exhibited a new dynamic technique for locating a point in a convex planar subdivision whose n vertices lie on a fixed set of N horizontal lines. The supported update operations are insertion/deletion of vertices and edges, and (horizontal) translation of vertices. Our method achieves query time O(logn+logN), space O(N+nlogN), and insertion/deletion time O(lognlogN). Hence, for N=O(n), the query time is O(logn), which is optimal. The proposed technique, based on the *trapezoid method*, provides an efficient solution to many significant applications where the most frequent operation is the point location query, while updates are more rarely executed.

By combining the first of the above techniques with the persistence-addition technique of Driscoll *et al.*, we have obtained the first three-dimensional point-location technique with query time $O(\log^2 n)$ and space $O(n\log^2 n)$ for a general spatial cell complex with n facets.

Finally, we have explored the implementation of (batched) planar point-location on a realistic parallel interconnection. The problem is stated as follows: Given a planar subdivision R induced by a plane graph G=(V,E), with $|V|=N$, and a set S of M points in the plane, we wish to locate in parallel S in R, i.e., for each point $p \in S$ we wish to find the region of R containing p. Assuming that $M=\Theta(N)$, we show that the task can be carried out on the cube-connected-cycles (CCC) architecture in time $O(\log^2 N)$ with O(NlogN) processors, or in $O(\log^3 N)$ with O(N) processors.

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## WORK UNIT NUMBER 16

TITLE: High-Resolution Sensor Array Processing

SENIOR INVESTIGATORS:

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SCIENTIFIC OBJECTIVE:

The term "sensor array system" refers to a large class of remote sensing systems in which data are collected and recorded by many independent sensors, or by one sensor that is moved to different spatial positions. The recorded data are processed by a digital array algorithm to produce a high-resolution object function. Some of the more important multi-sensor array systems now in use are synthetic aperture radar (SAR), computer-aided tomography (CAT), and beam-forming sonar. The objective of the research in this unit is to develop both the theory and computer verification of new signal processing methods with the goal of overcoming current limits on resolution and data throughput rates for these systems. Specifically, we propose to develop reconstruction algorithms that: (1) can achieve high resolution from a limited amount of sampled data; (2) have small enough computational complexities that real-time implementation is feasible; and (3) can be partitioned into sets of elementary operations suitable for VLSI realization.

SUMMARY OF RESEARCH:

During the past year our JSEP research has concentrated on two topics with potential applications to high-resolution sensor array processing: adaptive filtering and a frequency-domain approach to windowing and interpolation. This research is described below.

**Adaptive Filtering**

The LMS adaptive algorithm is the best known and most widely used real-time adaptive finite impulse response (FIR) algorithm due to its simple computational requirements and well-behaved convergence characteristics. However, as VLSI digital processors become cheaper and more readily available, the question arises as to whether more effective real-time algorithms and filter architectures can be found that take advantage of increased computational resources. For example, it is well known that in 1-D FIR filters the RLS adaptive algorithm converges much more rapidly than the LMS algorithm in nonstationary signal environments. However, the LS algorithm requires on the order of $n^2$ arithmetic operations per iteration, as opposed to an order of $n$ operations per iteration required by the LMS algorithm, where $n$ is the length of the FIR digital filter. It is also known that the use of infinite impulse response (IIR) adaptive filters may reduce the number of arithmetic

operations required per iteration, although poor adaptive behavior sometimes results from the nonunimodality of the error surface; instability may result from the poles of the IIR structure moving into unstable portions of the parameter space; and erratic behavior may result from sensitivity to quantization errors. Therefore, many research questions remain open regarding the best way to achieve reduced computational complexity while maintaining rapid convergence to the optimal conditions for both FIR and IIR adaptive filters.

Recently, new results have been obtained in three areas of adaptive signal processing: (1) 1-D IIR adaptive algorithms, (2) 1-D FIR adaptive filters, and (3) 2-D FIR adaptive filters. In the first area a new IIR algorithm was developed earlier under JSEP support by combining the well-known equation error method with an adaptive prefilter, creating a family of algorithms called the prefiltering (PF) algorithms. It was shown both theoretically and experimentally that the PF algorithms are capable of finding the global minimum error condition when operating on error surfaces that are not unimodal. Recently, the PF algorithms were shown to operate effectively in IIR echo cancellers [1], and a PF algorithm was developed for a cascade IIR filter structure that converges much more rapidly than direct forms.

In 1-D FIR adaptive filtering, new algorithms were created by combining different orthogonal transforms (the discrete Fourier transform (DFT), the discrete cosine transform (DCT), the Walsh-Hadamard transform (WHT), the discrete Hartley transform (DHT), and a specially designed power-of-2 transform (PO2T)) with an adaptive FIR structure to improve learning characteristics. The transforms provide a real-time decomposition of the incoming signal into a set of partially uncorrelated components. Power normalization and subsequent adaptation on the individual components lead to faster convergence rates when the adaptive system operates in a colored noise environment. This early work on orthogonal transforms eventually led to a new quasi-Newton FIR algorithm that is effective in achieving near-optimal convergence rates when the input statistics are not known *a priori* [3,5]. Use of a Toeplitz autocorrelation matrix estimate allows this new quasi-Newton algorithm to achieve a reduced computational complexity similar to the RLS algorithm, but it has been shown to be much more robust with respect to finite wordlength effects.

In the area of 2-D FIR adaptive filters, a new adaptive filter was proposed based on the McClellan transformation design technique for 2-D filters [6]. It was first shown that if the transformation structure is constrained by *a priori* knowledge of contour shapes in the frequency domain, the 2-D adaptive algorithm greatly reduces computational requirements and leads to more rapid learning characteristics, as compared to a conventional 2-D LMS algorithm. An extended form of the new algorithm was also proposed in which the contour parameters were included in the adaptive parameter set, thereby removing *a priori* constraints on the frequency domain contours. Recently, an orthogonal transform was added to the constrained transformation structure to improve the convergence rate through decorrelation and power normalization, similar to the technique applied earlier in 1-D FIR adaptive filters. In general this new approach to 2-D adaptive filtering represents a breakthrough that has yet to be fully investigated.

### Frequency-Domain Approach to Windowing and Interpolation

Standard windowing techniques, such as truncation and Hamming windowing, form the windowed sequence by multiplying the input sequence with the window sequence in an element-wise fashion. As such, these are examples of simple linear time-varying (LTV) systems. In [7] we have studied windowing from a more general LTV systems point of view, where each element in the windowed sequence is a linear combination of the elements in the input sequence. Thus, we have considered a window matrix rather than a window sequence. This generalization suggests the use of a LTV frequency domain representation to both design and characterize different windows. This Fourier representation allows information about the original signal to be incorporated into the window design procedure so that the windowed signal can more accurately retain Fourier domain features. We have used this representation to design generalized windows using a weighted $L^2$ frequency-domain error norm. Such windows may have application in windowing sensor-array data prior to Fourier inversion.

We have also recently begun work on a new frequency-domain approach for the problem of interpolation from non-Cartesian sampled data [8]. Such problems arise in SAR, tomography, and in other sensor-array systems. Our approach uses a linear time-varying systems framework to develop a frequency-domain methodology for both characterizing and designing algorithms for interpolation from nonuniformly spaced data. Although much work remains to be done, it appears that this methodology may represent a real breakthrough for dealing with this difficult problem.

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## WORK UNIT NUMBER 17

TITLE: Parallel VLSI Structures for Sensor Array Processing

### SENIOR INVESTIGATORS:

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### SCIENTIFIC OBJECTIVE:

The research in this unit is motivated by the observation that modern signal processing cannot be done in real-time on a single sequential processor. To achieve real-time operation, signals generated by sensor-array systems must be processed in a pipelined and/or parallel mode using a large number of fast, dedicated processors working in unison. The objective of this work unit is to develop high-throughput, VLSI structures for the real-time implementation of high-resolution algorithms developed in work unit 16 for sensor-array systems such as synthetic aperture radars, beam-forming sonars, direction finders, and x-ray CAT scanners.

### SUMMARY OF RESEARCH:

Research on this unit for the period April 1, 1988 through March 31, 1989 has concentrated on (1) VLSI architectures for 2-D adaptive filtering, (2) mapping of nonserial and nonlinear algorithms to multi-processor structures, and (3) the application of RNS arithmetic to modular VLSI design.

During the past year, we have devoted considerable time and effort to the study of VLSI architectures for 2-dimensional adaptive digital filters, which are becoming popular in image modeling and noise cancelling for robotics and computerized vision applications. The objective of this work is to develop 2D adaptive algorithms that converge quickly, have computational requirements that are low enough for real-time video rates, and are robust with respect to short wordlength and unknown signalling conditions. Our most recent efforts have been to develop a 2D lattice filter. We have derived a 2D lattice architecture and have obtained experimental evidence of rapid convergence rates. Results show that the noise floor is surprisingly high for the 2D adaptive lattice.

Also during the past year, we have studied two research problems on mapping nonserial and nonlinear algorithms, which are important in signal processing applications, onto regular VLSI arrays and multiprocessors. Using a 3-dimensional VLSI model, we derived tight bounds on mapping algorithms onto such a model [6,9]. These bounds are useful in comparing the cost-effectiveness between implementations using 2-dimensional and those using 3-dimensional technologies. A second research problem involves mapping neural network simulation algorithms onto VLSI arrays and multiprocessors. We have developed an optimization model of such a mapping problem and have experimented on mapping the back-error-propagation learning algorithm on the Intel iPSC-16 processor system, a

network of SUN systems, and a mesh of VLSI array. A technical report is currently under preparation [10]

We have continued to study the application of RNS arithmetic to designing VLSI modules that can be used for high-resolution sensor array processing. Early attempts at VLSI implementation of modular arithmetic units for signal processing applications were necessarily based on binary arithmetic. However, with the advent of VLSI technology, it has become possible to develop modular arithmetic units based on RNS arithmetic that are designed and optimized for their specific tasks, as opposed to make-do existing designs [7]. In our current work, we have begun to further develop the concept of a special, bit-level, systolic cell that was first introduced by Jullien and ourselves [8] for implementing the inner-product step processor (IPSP), which is a modular multiply-accumulate cell. Our work has further developed a modular, bit-level, systolic cell realization of the IPSP that allows modular implementations of linear signal processing algorithms to be constructed from large systolic chains of these cells. This will ultimately lead to a true generic cell implementation of DSP algorithms. Circuit design has been completed for a generic cell that contains error detection internally. The IC design has been sent to MOSIS for fabrication.

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## WORK UNIT NUMBER 18

TITLE: Adaptive Algorithms for Identification, Filtering, Control, and Signal Processing

**SENIOR INVESTIGATORS:**

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**SCIENTIFIC OBJECTIVE.**

Our group has been and is in the forefront of research on a wide array of problems in adaptive systems; some of the problem formulations, methods, and results that have originated in our research group have been accepted by leading researchers worldwide and are being experimentally tested. This accumulated experience and knowledge in the field puts us in the best position to address the underlying fundamental issues and to develop a theory for adaptive algorithms that operate in partially modeled environments.

Our approach embodies the philosophy that adaptive systems, be they adaptive filters, estimators and controllers, or diagnostic and tuning software for automatic quality control and maintenance, are logical on-line extensions of well-tested off-line algorithms and, as such, should inherit their robustness properties. To achieve this level of realism, we allow our convergence and stability conditions to be signal-dependent and guarantee them in the domain of interest, rather than globally. This closes the gap separating the realistic conditions from the mathematically appealing global results derived under unrealistic and unverifiable modeling assumptions. The robustness properties guaranteed by our approach will compensate for the loss of fictitious globality.

Toward this general objective, one of our goals in this research project is to investigate the key question of whether there are *self-tuning* algorithms with the important feature that the algorithm will automatically tune itself to a correct regulator for a given unknown system. Earlier versions of such algorithms have had a big impact on the practical control of a certain class of systems and are also beginning to be fabricated on chips and installed in industrial plants, vehicles, ships, and other communication and control equipment.

Our second goal is to examine the behavior of the algorithms in a variety of environments where precise modeling assumptions are violated. Following the first encouraging results, one of our objectives is to develop a methodology to design algorithms that are capable of using the available *a priori* information about systems to be identified, estimated and/or controlled, and to avoid limitations imposed by preselected parameterizations. We instead plan to use existing physical parameters and thus enhance not only robustness but also serviceability of the control instrumentation.

**SUMMARY OF RESEARCH:**

On the issue of self-tuning, we have very recently obtained a new procedure called "Bayesian embedding" that enables the analysis of a variety of least squares schemes, without requiring a tedious and often futile search for stochastic Lyapunov functions [11]. This methodology clearly shows the convergence of parameter estimates and provides a unifying framework for obtaining diverse results such as optimality proofs, the delineation of the limiting parameter estimates, the role of persistency of excitation, and the exploitation of large delays. This theory requires an extension of the well-known Kalman Filter to the case of systems with random matrices [12].

Reduced-Complexity adaptive control is a research topic of major practical interest that poses problems of increased theoretical complexity. The goal is to improve convergence properties and robustness of adaptive controllers by updating only a few "crucial" parameters. Our two approaches recognize that a search for "crucial" parameters is both structure-dependent and problem-dependent and hence must rely on a considerable amount of prior information. A major result of the first approach [4,10,13,14] is a new parameterization independent of system order and with a structure that allows the deviation of a well-defined error system. The second approach [7,15] is problem-dependent and is applicable to "tuning-conflict" situations, common in industrial control systems. Three types of conflicts are characterized and an off-line averaging procedure is used to search for conflict-resolving parameters. The procedure is based on the prior knowledge of the existence and attractivity of a particular integral manifold.

We have shown in [5,6,8] how to obtain an adaptive controller that is optimally performing under ideal conditions, but that also is robustly stable to small perturbations with respect to the graph topology on the space of systems. Since the graph topology has previously been identified as the weakest topology with respect to which one can preserve stability and continuity of frequency response even in known linear systems, this result shows that in principle no local robustness need be sacrificed for performance.

Development has continued on the projective controls techniques for design of low-order controllers [1,2,3,9]. Emphasis has been placed on controller robustness to plant and disturbance uncertainities such as unmodelled dynamics and unknown disturbance inputs. A new parameterization of the closed loop systems in terms of the parameters in the projective controller has been formulated. The Frobenius-Hankel (FH) norm has been selected as a measure of disturbance response, and the minimization of the FH norm with respect to the projective controller parameter has been proposed as a design approach. Both Lyapunov-based and Riccati-based numerical methods have been examined for FH norm optimization.

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## WORK UNIT NUMBER 19

**TITLE:** Distributed and Decentralized Systems

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**SCIENTIFIC OBJECTIVE:**

Attempts to harness several newly emerging technologies, which lead naturally to large-scale, computer-controlled systems, have given rise to a significant interest in the underlying field of distributed and decentralized systems. Most of these systems incorporate task decomposition, multilevel coordination and control, and distributed estimation and computation. Some of them diverge from classical systems in that the basic phenomena governing them are event-driven and discrete. Examples of such event-driven systems are many and include automated VLSI production systems for making printed circuit boards or fabricating wafers in large volumes in flexible electronic assembly systems, communication networks for data transmission, and interconnected computer systems. They require descriptions in terms of discrete quantities such as the number of PC boards to be retested, or other dynamic, logical and linguistic variables; and they operate as event-driven, asynchronous, largely nondeterministic processes, and hence must be analyzed as such. The basic goal in studying such large, complex, and, typically, distributed and decentralized systems is, firstly, to design them for efficiency and then to control and coordinate them to attain this efficiency. Important issues that arise in the modeling, control, and coordination of such systems are information flow, learning, aggregation, time scale separation, decentralized estimation, and distributed computation. The principal objective of this research unit is to study such issues in order to enhance our understanding of the behavior and control of large-scale, computer-controlled systems in a distributed network, under uncertainty and decentralization.

**SUMMARY OF RESEARCH:**

An important aspect of decentralized and distributed large-scale systems is that all decision makers who provide input to the system may not adopt precisely the same model of the overall system, and some might even consider simplified lower-order models that are most relevant for their control and optimization. Therefore, a realistic study of such systems should use a framework that allows for discrepancies between individual models, some of which may be of a probabilistic nature. Such a framework was first introduced in our earlier JSEP paper [31] that also analyzed, in the context of static problems, the robustness and sensitivity of team-optimal solutions to deviations in the perceptions of the decision makers from a common stochastic model. In a recent paper [8], we have

considered dynamic decision problems, modeled as continuous-time stochastic differential games with linear dynamics, where the decision makers are allowed to develop different prior probabilities on the random variables appearing in the system dynamics and the measurements available to each decision maker. We have obtained precise conditions for the existence and uniqueness of symmetric noncooperative (Nash) equilibrium and have developed a method for iterative distributed computation of the corresponding policies. The distributed algorithm involves learning in the *policy space*, and it does not require that each decision maker know the others' perceptions of the probabilistic model underlying the decision process. For the finite-horizon problem, such an iteration converges whenever the length of the time horizon is short, and the limit in this case is an affine policy for all decision makers if the underlying distributions are Gaussian. When the horizon is infinite, and a discount factor is used in the cost functionals, the iteration converges under conditions depending on the magnitude of the discount factor, the limiting policies again being affine in the case of Gaussian distributions.

In the problem of the optimum joint design of measurement and control policies in stochastic systems, our efforts culminated in the paper [10], which first shows that such problems are basically stochastic dynamic teams with nonclassical information for which no applicable theory exists. However, using an indirect approach, the problem is completely solved in [10] for first-order systems under a quadratic cost criterion. We show that, in the case of hard power constraints, the optimal measurement policy consists of transmitting the "innovation" in the new data at the maximum power level. In the case when the power levels on the measurements are not fixed, the optimal power levels for transmitting this innovation can be found by solving a nonlinear optimal control problem, a solution to which always exists. When the time horizon is infinite and the cost functional is discounted, there exist optimal stationary control and measurement strategies, and they can be obtained again from the solution of a (stationary) nonlinear optimal control problem. The paper provides an algorithm to compute the solution and also develops the best linear policies when the system is of higher order.

On the topic of minimax design philosophy, we have developed a number of theoretical results on robust (saddle-point) solutions for stochastic optimization problems with incomplete statistical description and decentralized information, with one source of motivation being jamming problems arising in communications; see [6,9]. We have studied both discrete-time and continuous-time systems and have obtained minimax rules in all cases, some leading to saddle points and others not.

Another topic of research undertaken during the past three years is simulated annealing. Many, typically intractable, optimization problems are characterized by the existence of several local minima, in addition to the desired global minimum. For such problems, we have investigated [3,11] the recently proposed method of optimization by simulated annealing. In essence, this method is a modification of standard descent schemes that occasionally accepts uphill moves with a certain probability dependent on the magnitude of the uphill movement as well as a small parameter that is analogous to "temperature." This algorithm gives rise to a time-inhomogeneous Markov chain with transition probabilities proportional to power of the vanishing small parameter. It is clearly of considerable interest to analyze the asymptotic behavior of such processes to determine conditions under which the algorithm hits a global minimum. In [3] we have obtained the necessary and sufficient condition on the cooling rate in order to guarantee hitting the global minimum with probability one. This is done by a new theory of "balance of recurrence orders" for the general class of such Markov chains. In [9] we have obtained procedures to determine recurrence orders, as well as to generalize our earlier result to the case when the neighborhoods in the optimization problem are not symmetric.

In another recent paper, [5], we have studied the problem of dynamic scheduling of flexible manufacturing/assembly/disassembly systems. Such systems can consist of a variety of part-types that need processing at a specified sequence of machines in the system. The goal is to produce all part types at certain desired rates, while maintaining bounded and small buffer sizes at the machines. There are two complications: (1) the machines may incur a set-up time when changing between part-types; (2) parts incur a variable transportation delay in moving from machine. Our main contribution is the development of a theory of distributed real-time scheduling that achieves the above

objectives. It also determines some fundamental performance limitations for such manufacturing systems. The philosophy of the paper is to study the roles of dynamics, feedback, and stability in such discrete-event systems.

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## WORK UNIT NUMBER 20

TITLE: Robust Feedback Control of Nonlinear Systems

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SCIENTIFIC OBJECTIVE:

For physical devices running the gamut from rotating machinery to opto-electronic laser positioning systems, nonlinearities constitute an essential part of any reasonable model. Revolutionary developments in microelectronics, coupled with recent breakthroughs in the understanding of the structural properties of nonlinear dynamic systems, open up new possibilities for the synthesis and implementation of feedback controllers in order to meet the steadily rising needs for higher performance and increased efficiency. However, even the most powerful analytical tools that are available today, such as exact linearization via feedback, nonlinear input-output characterizations, and geometric conditions for noninteracting control and disturbance rejection, still require that exact nonlinear models be available. This is in direct conflict with the fact that the mere presence of nonlinearities makes accurate modeling and identification difficult. Consequently, controllers based upon the currently available theory could be highly unreliable.

To remedy this situation, some fundamentally new lines of research are needed for the design of realistic robust controllers for nonlinear systems. Driven by this need, our research program has two key objectives. The first is to develop a fundamentally new *geometric-asymptotic* approach for the synthesis of robust nonlinear controllers; this approach will combine the advantages of exact geometric notions with estimates of sensitivity and robustness obtained from an asymptotic analysis and will build upon synergisms of two types of expertise available within our research team. The second objective is to deal with circumstances where desired levels of performance *cannot* be achieved by feedback; it is then necessary to restructure the nonlinear systems. Our objective here is to develop a methodology for reconfiguring nonlinear systems for robustness enhancement.

SUMMARY OF RESEARCH:

On the problem of developing robust systems, we have pursued research in the parallel directions of integral manifold analysis and nonlinear design with unmodeled dynamics.

An "in-manifold" analysis has revealed a possibility to preserve global boundedness even when the tuned parameter equilibrium is unstable. This encouraging result stimulates further investigations into the relationship of local and global robustness properties. We have also exploited integral manifolds as nonlinear decomposition tools for a class of tracking problems, including nonlinear PI controller design. A similar tool was used to develop a hierarchy of reduced order models.

Nonlinearities and unmodeled dynamics have been treated by a novel geometric-asymptotic method. A preliminary robustness result is obtained for the special case when, in spite of parametric uncertainty, there exists a parameter-independent state-diffeomorphism leading to adaptive feedback linearization. The restrictiveness of this assumption is relaxed by allowing its violation in a faster time-scale due to unmodeled dynamics. An actual power electronics application of this design method has been described. A broad set of issues faced by feedback linearization under uncertainty has been identified. A nonlinear sampled-data problem has been solved.

We have shown that one can obtain adaptive robust control by doing on-line switching between families of robust control laws. This adaptive controller has the maximal possible robustness margins.

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## WORK UNIT NUMBER 21

TITLE: Multiple-Terminal Digital Communication Systems

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**SCIENTIFIC OBJECTIVES:**

Problems involving the interaction of the elements of a multiple-user communication network are among the most important and most challenging problems in electronic communications. The performance of a communication network depends in a very complex way on the routing algorithm, flow control mechanism, acknowledgment procedure, channel access protocol, error-control code, signaling scheme, receiver processing method, and synchronization technique employed in the lower three layers (network layer, data link layer, and physical layer) of the ISO-layered model for the network. The objective of our research in multiple-terminal digital communications is to gain a better understanding of the interplay between these elements. Our research will focus on the issues that arise in mobile radio networks, particularly spread-spectrum radio networks, that must operate in hostile environments that include jamming and fading. This imposes additional requirements on the network in terms of robustness and survivability that will be accounted for in our research.

One of the objectives of our research is to develop new signaling methods and receiver processing techniques that will exploit the implicit and explicit redundancy that is present in the signals and messages. Such redundancy exists in the physical layer (diversity transmission, multipath signals, and modulation), the data link layer (error control coding), and the network layer (redundant packets and messages). We are particularly interested in the efficient use of implicit and explicit diversity in spread-spectrum radio transmissions to improve communication performance under stressed conditions (e.g., jamming or heavy network traffic). Another objective is to develop network protocols that are compatible with and take advantage of the features of spread-spectrum modulation. Of particular interest are algorithms for distributed scheduling of transmissions. A third objective is to examine the synchronization problem for spread-spectrum radios. Efficient network operation requires fast acquisition of the spread-spectrum signals. Moreover, the acquisition and synchronization systems must be able to operate in the presence of multiple transmissions, jamming, and fading to be of any use in a military communications network.

## SUMMARY OF RESEARCH:

### Meteor-Burst Communications

In a meteor burst communication system, the received power level typically decays exponentially with time as the meteor trail disperses. Thus, the trade-off between error probability and message transmission time is rather complicated, and it is necessary to adapt the transmission time to the decay characteristics of the channel. This has been the focus of our recent work on meteor-burst communications.

We have shown that higher throughput and lower error rates can be achieved by adapting the error-correcting code to the channel. There are two approaches to adaptive coding in this context: adaptive selection of a fixed-rate code from one trail to the next and adaptive variable-rate coding. Even if the code rate is fixed throughout the lifetime of a meteor trail, the fact that some trails decay faster than others should be accounted for in the selection of the code rate. In the simplest method, we employ a code of fixed rate throughout the life of the trail, but we vary the code rate from one trail to the next, which is inter-trail adaptation using fixed-rate codes. Use of this type of adaptation requires estimation of the decay rate for each meteor trail.

Our work to date indicates that even more can be gained by varying the rate of the error-correcting code during the lifetime of each meteor trail. In one scheme, initial estimates are made for the signal strength and decay rate, and the optimum sequence of code rates is determined for use on that trail. This could be classified as inter-trail adaptation using variable-rate codes. In most cases, the reflected power is very strong when the trail is first formed, so a code with a small amount of redundancy can handle the few errors that occur. Such codes will provide high throughput in the early phases of the meteor trail. As the trail expands and becomes less dense, however, the reflected power is reduced, and the error rate on the channel increases. As a result, more redundancy must be used during the latter phases of the trail's existence in order to correct the larger number of errors that occur. In contrast to this scheme, in which a sequence of rates for the variable-rate code is selected at the beginning of the trail, a true intra-trail adaptation scheme requires continual estimation of the signal strength and decay rate throughout the duration of the meteor trail. This approach will provide even better information for use in code rate adaptation, but it also demands more from the communication system.

The potential improvement for inter-trail adaptation using fixed-rate and variable-rate Reed-Solomon coding on the meteor-burst channel was investigated in [5] and [8] for both coherent and noncoherent communication. We assume that the signal strength decays exponentially, and the approach used for adaptation is based on a selection of the code rates for a packet to send a fixed number of information symbols. The rates selected depend on the estimates of the received power and decay rate obtained during the initial part of the packet. An optimal algorithm is given in [5] for selecting the set of code rates to be used to transmit a fixed number of information symbols on a given meteor trail. In comparisons of variable-rate codes and fixed-rate codes for inter-trail adaptation, the former were found to give performance improvements in the range of 0.5 to 1.0 dB over the latter. We found that the selection of the rates for the variable-rate code does not depend very strongly on the initial signal-to-noise ratio for the trail; it does, however, depend critically on the decay rate.

More general (intra-trail) adaptation can be implemented if the transmitting terminal continually monitors the signal strength at the receiver and adapts the code rate throughout the packet. This can be based on power measurements on the return channel or on feedback information from the receiver. Both of these require full duplex operation. The former also requires the link to be symmetrical and bidirectional, while the latter does not require the link to be symmetrical. The method developed in [5] can be applied at several stages during the decay of the meteor trail to give continual adaptation throughout the packet. A trade-off exits between the performance of the resulting variable rate code and the amount of computation required by the algorithm. More frequent application of the algorithm during the transmission of the packet requires more computation but also gives a code that is closer to the optimum.

**Diversity Combining Techniques for Noncoherent Communication**

We recently completed investigations of several new diversity-combining techniques for noncoherent communication over channels with fading and partial-band interference. These techniques all attempt to limit the impact of interference that may be present on one or more of the diversity receptions; and they are applicable, for instance, to frequency-hop spread-spectrum communication systems and networks that must operate in the presence of jamming, fading, and various forms of narrowband interference. Side information concerning the presence or absence of interference on the individual diversity receptions is not required for any of these diversity combining techniques.

Clipped-linear combining is a diversity-combining technique in which the envelope detector outputs are first clipped at some specified level and then added to form the receiver's decision statistics. In this approach, all diversity receptions are employed in forming the decision statistics. The purpose of the clipping is to limit the effects of strong partial-band interference. The practical disadvantage of this method is that the optimum clipping level depends on the signal strength, which may be unknown and difficult to measure in certain applications (e.g., mobile radio networks).

The ratio-threshold test (RTT) for diversity combining does not require knowledge of the received signal strength. In this method, a ratio statistic is formed for each diversity reception. This statistic is the ratio of the largest envelope detector output to the second largest. The ratio statistic is compared with a threshold, and a decision is made as to the presence or absence of interference. All diversity receptions that pass the RTT (i.e., are judged as not having interference present) are combined to form the decision statistic; those that fail the RTT are ignored. If all diversity receptions fail the RTT, then all of them are combined to form the decision statistic, even though this statistic may be erased later in the decoding operation. Two different combining functions were studied: square law and majority logic. In the former, the sum of the squares of the envelope detectors are added; in the latter, a decision is made on each envelope detector output to be combined, and a majority vote is taken. We found that the RTT with majority-logic combining was superior to the RTT with square-law combining as a method for combating partial-band interference in frequency-hop radios.

Ratio statistics can also be used in other ways for diversity combining. In [4], we proposed a technique, referred to as ratio statistic combining, in which the ratio statistics are themselves added to form the decision statistics. This method provides the effect of a clipping operation without the need to set a clipping level. We have compared the performance of this method with that of clipped-linear combining, the RTT with majority logic combining, self-normalization combining, and optimum diversity combining. Because optimum diversity combining requires side information (assumed to be perfect), it does not give an achievable lower bound on error probability, but it is a useful benchmark against which to compare the performance of proposed schemes. We found that ratio statistic combining is slightly better than self-normalization combining and that these two are superior to both clipped linear combining and RTT with majority logic combining if the interference occupies at least half the band of the frequency-hop signal. For interference of narrower b .ths, clipped linear combining is the most effective scheme of the four suboptimal techniqu .dered. All four techniques examined required at least 1.5 dB more signal power than optimal combining with perfect side information for the same error probability, regardless of the bandwidth of the interference. This suggests that there is still considerable room for improvement.

**Synchronization of Direct-Sequence Spread-Spectrum Signals**

We have studied the acquisition of synchronization in a direct-sequence spread-spectrum system via a sequential search technique with adaptive time-varying thresholds and varying dwell times. This scheme allows for false hypotheses about the signal epoch to be discarded relatively quickly and still achieves the same miss probability as schemes with fixed thresholds. Critical to the operation of this scheme is a uniform bound on the aperiodic autocorrelation of a PN sequence that allows false hypotheses to be rapidly discarded. We have also obtained considerable experimental evidence that our bound is quite weak and that our estimates of the time required to acquire synchronization are

rather pessimistic actual system performance should be much better than our estimates.

We have studied parallel acquisition techniques that consider multiple hypotheses about the signal epoch in order to reduce the acquisition time. In the case of a PN sequence code of period N, one correlator with an integration time of one chip can be used to compute N single chip correlations. The decision statistics are then just the Hadamard transform of these correlations If a complete period of the PN sequence is available, this scheme can be viewed in the context of orthogonal signalling, and the well-known results on orthogonal signalling can be applied to obtain results on system performance. However, we are interested in the effectiveness of this approach when fewer than N chip correlations are available, as would be the case when the PN sequence has a very large period and the delay in computing all N chip correlations is prohibitively large. This problem is complicated because when the Hadamard transform of a partial period is computed, the decision statistics are no longer independent random variables. The results on nonorthogonal signalling are, of course, applicable but not particularly useful in that the bounds on system performance that are obtained are rather weak. We have obtained some simple and better results by more detailed considerations of the structure of the PN sequence.

In the course of our investigations into parallel acquisition methods, we were able to obtain an improved bound on the error probability for M-ary orthogonal signaling in additive white Gaussian noise. The classical bound is the union bound, which is tight for high signal-to-noise ratios but is useless at low signal ratios. In fact, as the signal-to-noise ratio approaches zero, the union bound approaches $(M - 1)/2 > 1$. In contrast, our new bound is tight at low signal-to-noise ratios and approaches $1 - 1/(2M - 1)$ as the signal-to-noise ratio approaches zero. By symmetry considerations, the error probability is $1 - 1/M$ at zero signal-to-noise ratio. Thus, the new bound behaves much better that the union bound. We have also been able to show that the new bound is superior to bounds obtained by Gallager for all nonzero signal-to-noise ratios. Details are given in [6].

**Distributed Communication to a Receiver Employing Emission Control**

We have investigated the problem of using a distributed communications protocol for accessing a silent radio receiver [9]. Our work expands on recent work of Wieselthier, Ephremides, and Tarr [22] that considers a scenario in which several packet radio users each wish to send a packet of information to a silent destination station. The time axis is divided into frames with M slots per frame. Each user transmits its packet Q times using spread-spectrum transmission, in Q pseudorandomly chosen slots. The receiver is assumed to know in which slots each user will transmit before the frame begins. The receiver computes an assignment, which is a choice of which user to listen to during each slot. Assuming perfect receiver selection capability, the size of the assignment is the number of successfully received packets.

We considered three assignment strategies, including the sequential-by-user assignment originally considered by Wieselthier et al. in which the receiver sequentially examines the users and assigns them to slots, and the strategy that generates the maximum throughput. We considered the assignment strategies as the number of slots M tends to infinity, while the number of users is $\alpha M$ so that the number of users per slot tends to $\alpha$. We gave methods to readily compute the asymptotic average utilizations for the three assignment strategies, using the theory of "slow Markov chains." For $Q = 2$ and $\alpha$ in the range $0.5 \leq \alpha \leq 1.0$, the maximum assignment is about 10% larger than that found by the sequential algorithms, while for other values of $\alpha$ the difference is smaller. The throughput for the maximum assignment strategy with $Q = 2$ is close to that for the sequential algorithm with $Q = 3$, so that less secondary interference need be generated when maximum assignment is used. Another advantage of maximum assignment we discovered is that, as the frame size increases, if the number of users per slot is below a threshold then the fraction of lost packets tends to zero.

**Load Balancing for Transmission Scheduling**

During the past year we derived an analytical method for the performance analysis of a load balancing algorithm [10] While the problem of load balancing is of intense interest due to the desire

to fully utilize processors in multi-task computing systems, little is known beyond simulations, about the performance of balancing algorithms. Our work provides new and significant progress in that direction. We originally conceived of the balancing algorithm for the problem of scheduling transmissions in a spread spectrum packet radio network in order to use locally available information to reduce the effects of secondary interference. However, we can formulate the problem in more generic terminology: A set of M resource locations and a set of aM consumers are given. Each consumer requires a specified amount of resource and is constrained to obtain the resource from a specified subset of locations. We also consider the problem of assigning consumers to resources so as to balance the load among the resource locations as much as possible.

It is shown that there are assignments, termed uniformly most balanced assignments, that simultaneously minimize certain symmetric, separable, convex cost functions. Algorithms of both iterative and combinatorial type are given for computing the assignments. The distribution function of the load at a given location for a uniformly most balanced assignment is studied assuming that the set of locations each consumer can use is random. An asymptotic lower bound on the distribution function (conjectured to be asymptotically exact) is given for M tending to infinity, and an upperbound is given on the probable maximum load. It is shown that there is typically a large set of resource locations that all have the maximum load and that for large average loads, the maximum load is near the average load.

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## WORK UNIT NUMBER 22

TITLE: Statistical Signal Processing in Communication Systems

SENIOR INVESTIGATORS:

H. V. Poor, Research Professor
A. R. Barron, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

B. Clarke, Research Assistant
S. Zabin, Research Assistant

SCIENTIFIC OBJECTIVE:

Statistical signal processing functions such as signal detection, estimation, and identification play a key role in the development of effective communications, radar, and sonar systems. For example, advanced statistical methods are emerging as being particularly important in digital communications systems operating in channels corrupted by interference from such phenomena as multiple-access noise, intentional jamming, and impulsive noise sources. Conventional demodulation methods, such as coherent matched filtering, often suffer serious performance degradation when subjected to interference of these types; however, this degradation can frequently be eliminated through the use of more sophisticated signal processing techniques.

A central issue in the design of effective signal processing procedures for systems operating in channels such as those noted above is that of channel identification. Although certain aspects of channel identification have been studied extensively, one area in which there is a pressing need for further research is that of identification of impulsive channels. Natural impulsive phenomena are major noise sources in many types of channels including ELF electromagnetic and under-ice acoustic channels. Moreover, man-made impulsive phenomena are a principal background noise source in the environments in which military radio networks must operate. Thus, since it is well established that impulsive noise can be extremely detrimental to the performance of communications, radar, and sonar systems if not properly suppressed and since impulsive channels often exhibit nonstationary characteristics, the development of effective techniques for identification and tracking of the characteristics of impulsive noise channels is an important problem in the development of systems that can approach the performance limits set by such channels.

The overall objective of this research project is to study the general problems of identification and tracking of impulsive channels. A thorough study of this area is planned, including the development of suitable channel models, the derivation and analysis of optimum batch and recursive nonlinear estimation algorithms for identification/tracking, and the application of these algorithms to develop adaptive techniques for the reception of signals passing through impulsive channels. It is anticipated that the results of this study will find application in a broad class of areas including digital communications, sonar, and radar.

## SUMMARY OF RESEARCH:

Our research efforts during this reporting period have focused on the development of algorithms for fitting the widely accepted parametric Middleton Class A impulsive noise model to channel measurements. Significant progress has been made on this problem during the past two and one-quarter years, as reported in [1-5]. In particular, we have developed efficient and practical batch procedures for intermediate-sized samples of channel measurements [4]; effective global recursive algorithms for channel tracking [1,5]; and, quite recently, efficient batch algorithms that give excellent performance for small sample sizes [3]. This group of algorithms utilizes the full spectrum of applicable point estimation methodology, including the method of moments, the method of maximum likelihood, decision-directed adaptivity, and the expectation-maximization (EM) algorithm, as well as ad-hoc techniques based directly on physical interpretations of the channel parameters. During the remaining six months of the current three-year cycle, work on this problem will be completed. Current activity includes the exercise via simulation of the EM algorithm for channel identification and the exploration of improved method-of-moments estimators based on the extraction of generalized (population) moments chosen for their sensitivity to the channel parameters.

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## WORK UNIT NUMBER 23

TITLE: Basic Research in Electronics

PRINCIPAL INVESTIGATOR:

W. K. Jenkins, Director and Research Professor

### SCIENTIFIC OBJECTIVE:

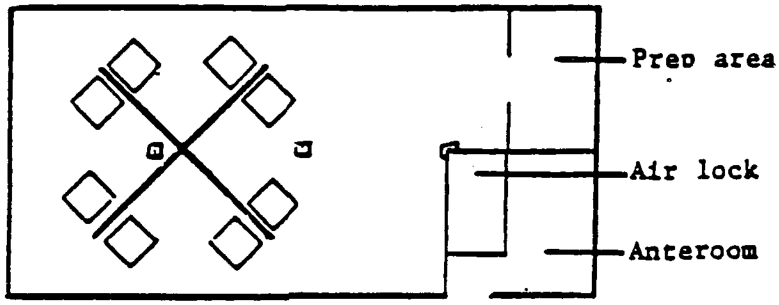
The objective of this unit is to provide discretionary funds to the Director for support of new initiatives on basic problems of electronic materials, devices, and systems in a timely manner and to provide early start-up funding of projects that present immediate opportunities of high scientific promise. These discretionary funds are an important feature of the JSEP program in that they support exploratory work on new topics, provide matching equipment funds in the laboratory, and support promising work of new faculty where appropriate.

### SUMMARY OF RESEARCH:

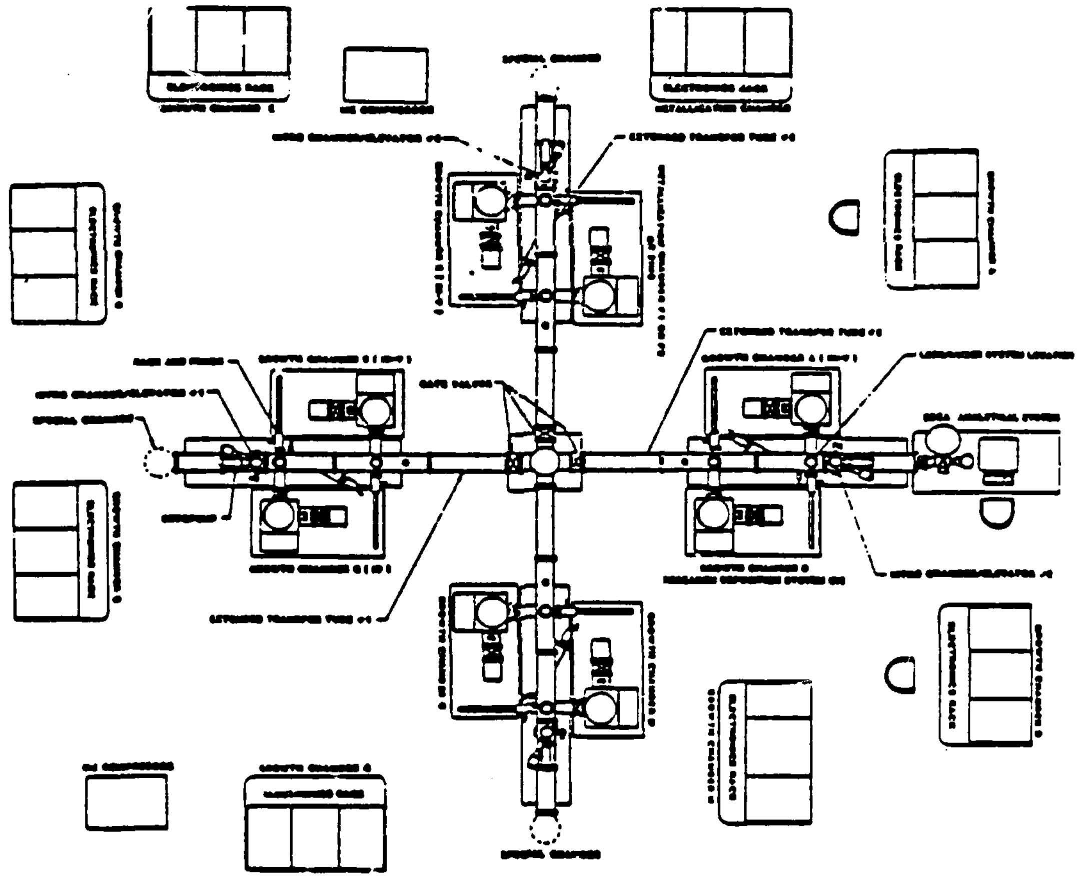
During the last three years, the entire Director's Fund of $300K was allocated to the new MBE "octopus" facility that is located in the east wing of the Coordinated Science Laboratory. This facility is jointly supported by CSL, the Materials Research Laboratory (MRL), and the Microelectronics Laboratory. These funds were applied toward the purchase of two MBE chambers that will be operated under the direction of Professor Joseph Greene and Professor James Kolodzey for future JSEP work. In addition to JSEP funds, CSL contributed $200K of indirect cost funds for equipment purchases. Also, during the past year CSL has allocated an additional $37K of indirect cost funds toward an operating fund that was budgeted at a total of $100K during 1988. The operating budget pays the salary of a full-time research engineer, who maintains the facility, and covers various facility expenses incurred for the installation and maintenance of the equipment. Construction of the facility was completed during the fall of 1988, and a dedication ceremony was held in November 1988 to mark its opening. Several of the MBE chambers are now operating, although the facility will not be in full-scale operation until later this year.

A team of researchers from the University of Illinois at Urbana-Champaign designed this unique facility in which state of the art surfaces, interfaces, and multilayers can be synthesized. This new facility is called the **EpiCenter**, an abbreviation for the U of I CSL-Microelectronics Joint Center for Epitaxial Growth and Surface Science. Approximately $500K was allocated from University of Illinois at Urbana-Champaign DOE Program funds for the purchase of the MBE equipment over FY 86, 87, and 88. The remaining funds for the $6M facility were contributed by NSF/Materials Research Laboratory ($500K), NSF/Engineering Research Center ($200K), CSL ($500K), AFOSR ($600K), and the University of Illinois at Urbana-Champaign, together with a gift from the Perkin Elmer Corporation of approximately $2.3M.

Seven MBE machines in the EpiCenter are interconnected by uhv ( $5 \times 10^{-11}$ torr) stainless steel transfer lines. From the same vacuum environment, it is possible to access advanced instrumentation for surface modification and sample characterization. The crystal growth equipment forms a cross at one end of the 80' x 40' facility. Access to the clean environment of the facility from an observation area is attained through an air lock, as indicated in Figure 1. A sample preparation room providing class 100 clean space in laminar flow hoods is accessible only from the main area. A lounge is provided for planning, discussion, computation, etc., during facility-related activities.




(a)



(b)

Fig. 1. Schematics showing (a) the EpiCenter facility for epitaxial growth and (b) the approximate layout of the MBE machines.

Both the MBE machines and the uhv transfer lines were fabricated by the Perkin Elmer Co. Figure 1b shows the configuration of the system. Machines 1 and 2 on Arm I are III-V compound machines with 2 adapted to gas-source research of Morkoc. Machines 3 and 4 on Arm II are designed for work with metals (3), with both effusion and e-beam sources, and for polar ceramic materials (4). Machine 5 is contributed by the University of Illinois at Urbana-Champaign Engineering Research Center for device work, and the other machine, 6, on Arm III is custom designed with e-beam hearths for research into growth of the group IV materials Si, Ge, etc. Finally, machine 7 on Arm IV is specially adopted to Greene's research using ion beam mixing to select particular growth paths of metastable structures. The complex thus contains a wide variety of crystal growth environments that are not ordinarily compatible with one another. Columns III and V elements, for example, are electrically active dopants in group IV semiconductors and must, therefore, be employed with selective care in group IV synthesis.

A special feature of the complex is that the seven machines are interconnected by uhv transfer lines held at a pressure of $5 \times 10^{-11}$ torr. The purpose is to permit transfer of a given substrate from one growth chamber to a second without surface contamination. This makes it possible to grow on a given fresh substrate an epitaxial layer which is not compatible with the environment needed to grow the substrate. The growth of GaAs on Si is a particular example of an important synthesis problem of this type. The seven machines offer a unique flexibility for research of this type into heteroepitaxy. In particular, the MBE and sample transfer equipment throughout is adapted to 3" wafers so that any sample may receive successive processing in any desired sequence of the seven growth chambers.

A variety of characterization and processing instruments are designed to attach on the ends of the arms. These, also, are fully adapted to the 3" wafer size of the synthesis complex. This permits *in situ* modification of samples and structure characterization within the common vacuum environment so that surface contamination is avoided. A substrate preparation chamber is attached to the end of Arm I so that substrates can be oxydized, sputtered, annealed, tested, etc. Opposite, on the end of Arm III, a rotating anode x-ray source and diffractometer are being set up for *in situ* studies of surfaces and multilayers. On Arm IV a PHI XPS unit is being installed for surface studies; its diagnostic capabilities are enhanced by added ion scattering spectroscopy, ultraviolet photoemission, and LEED capabilities. These are in addition to the RHEED and mass spectroscopy diagnostics in each MBE machine. Further, MBE machines 1, 3, and 7 are being specially equipped for ellipsometry, fluorescence, and other optical probes of film growth. Efforts are now being made to obtain Rutherford backscattering equipment for interface and surface studies on Arm IV of the system. A planned future development is the installation of focussed ion beam materials modification and an electron microscope on Arm I. Plans call for the experimental area at the end of Arm IV to become a surface science complex to which freshly grown surfaces from the complex can be transferred.